



The GEOS-5 Aerosol Forecasting and Data Assimilation System

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With contributions from Peter Colarco, Anton Darmenov, Virginie Buchard, Gala Wind, Cynthia Randles, Ravi Govindaradju and many others

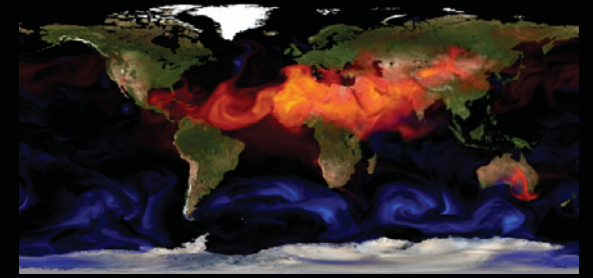
World Weather Open Science Conference
Montreal, Canada
16-21 August 2014

Outline



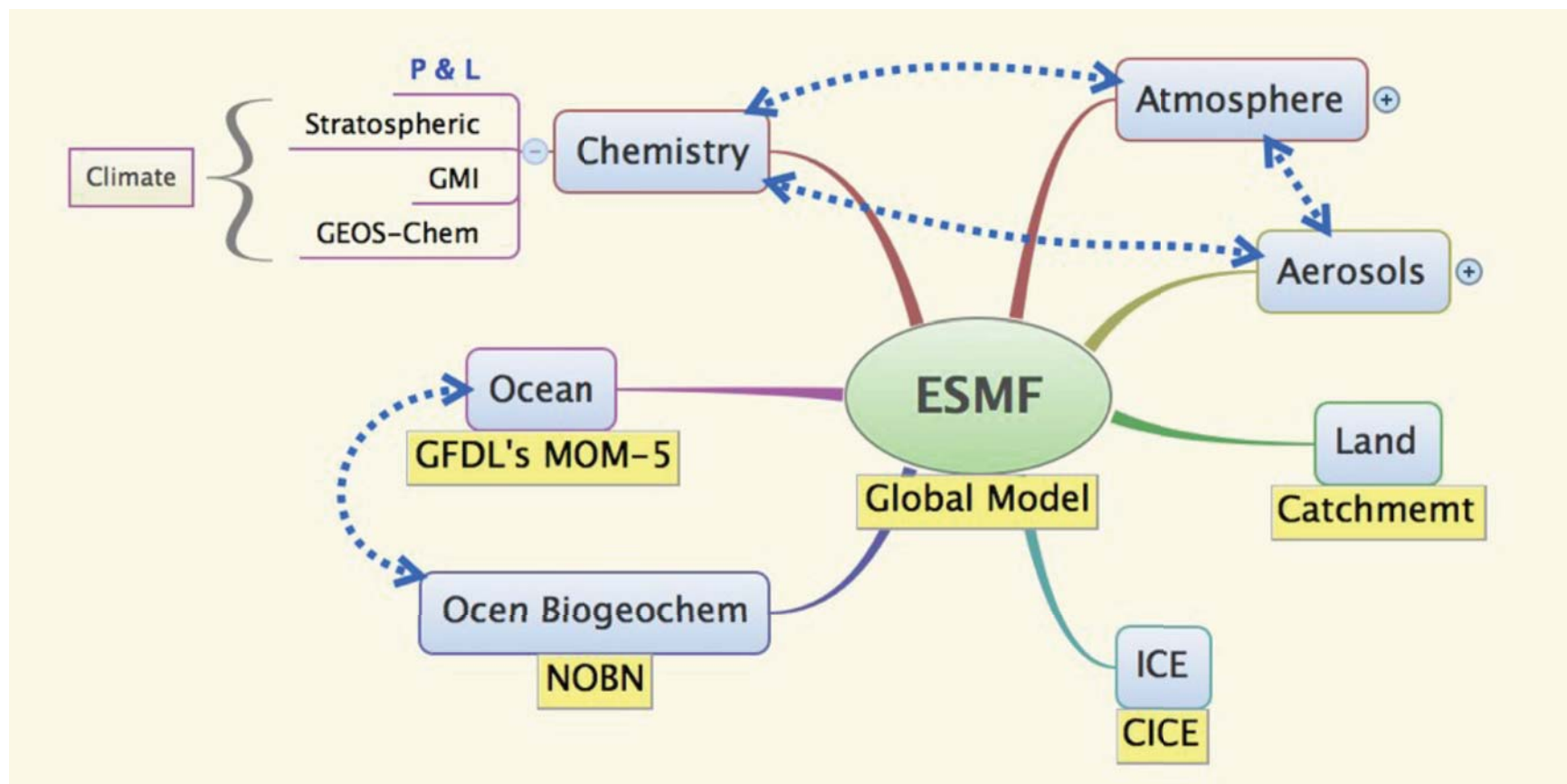
- GEOS-5 Overview
- Current capabilities and future directions
- Highlights:
 - Aerosol forecasting and field campaigns
 - Aerosol Reanalysis
 - OSSEs
- Concluding Remarks

Aerosol activities at GMAO



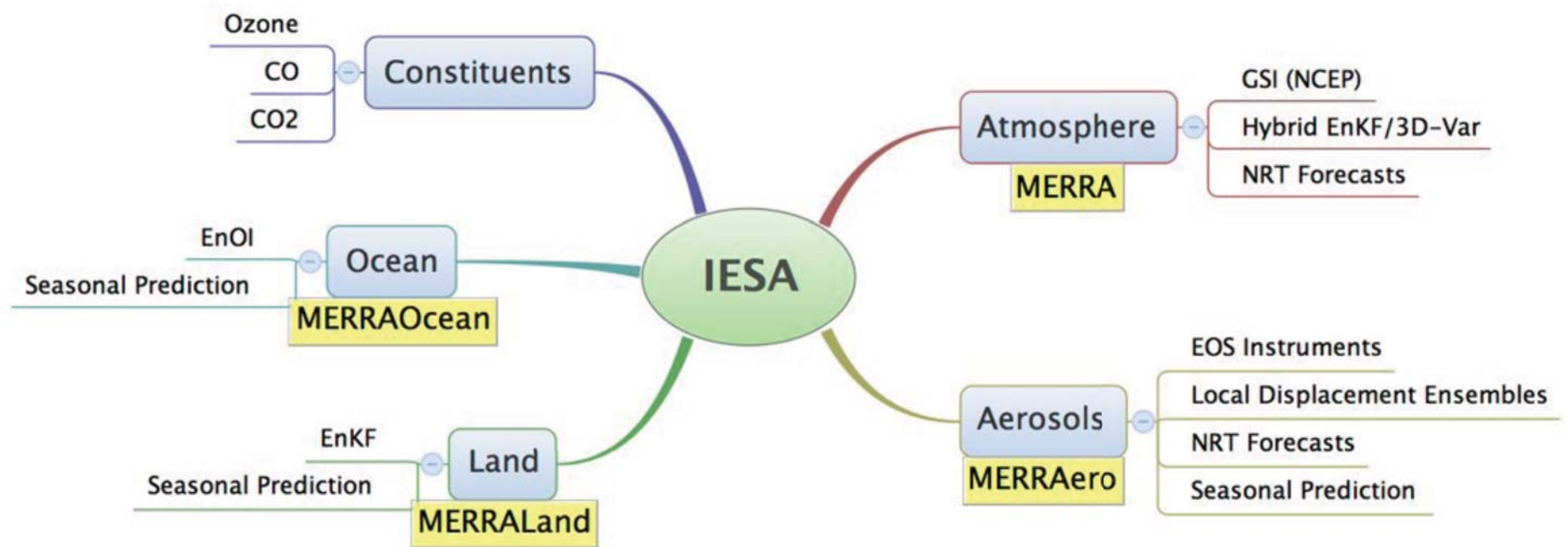
- Developing a **hierarchy of *global* models** capable of skillfully representing
 - the global aerosol distribution as depicted by available in-situ and remotely-sensed measurements
 - the microphysical processes needed for parameterizing cloud/precipitation-aerosol feedbacks
 - Aerosol interaction with earth-system components
- Developing a comprehensive **aerosol data assimilation capability** for constraining and calibrating aerosol transport models, including the estimation of emissions needed for driving such models
- Developing an **aerosol forecasting capability** in support of NASA field campaigns.
- Developing an **aerosol observing system simulation capability** for aiding planning of future NASA observing missions.

GEOS-5 Earth System Model

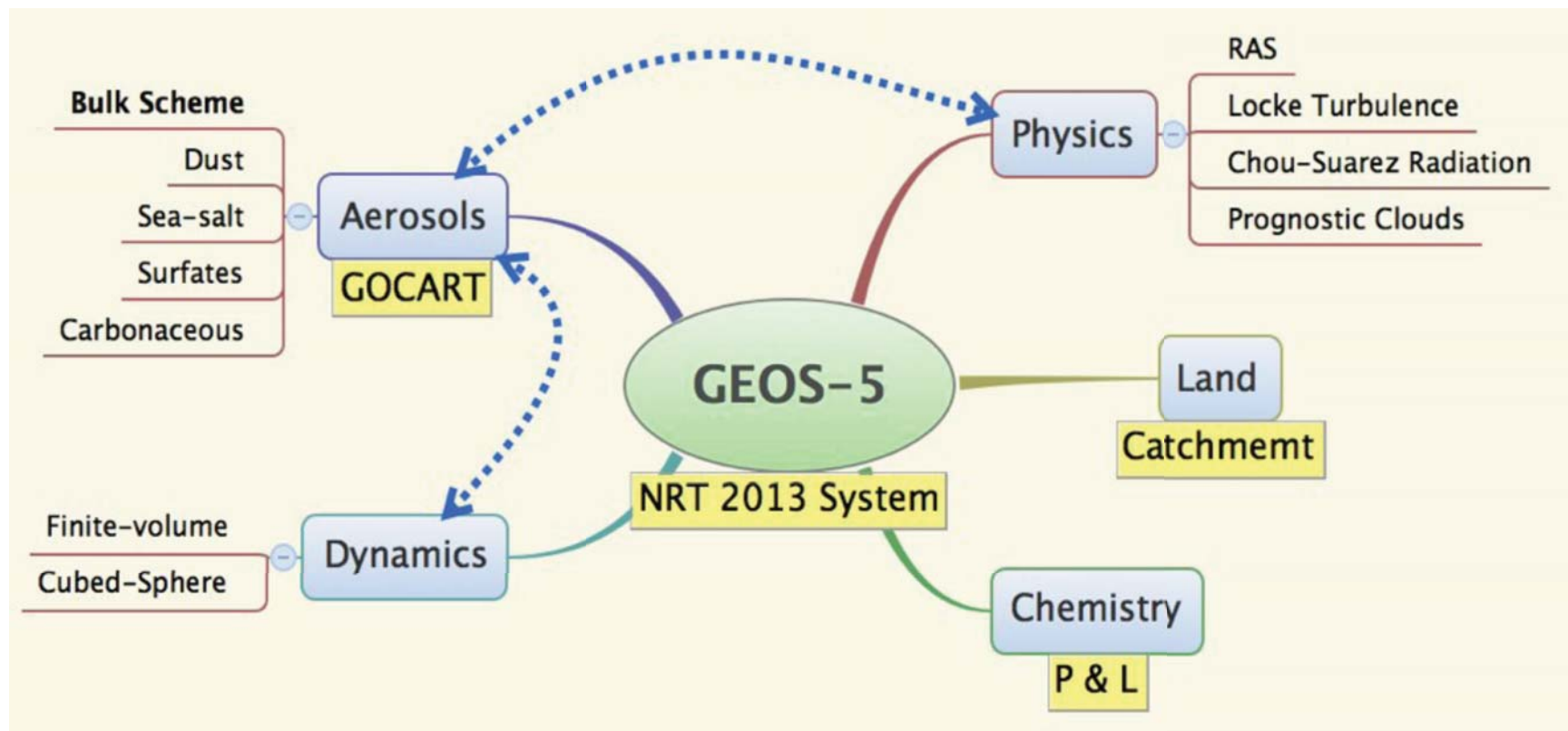


From weather to seasonal to decadal time scales

GEOS-5 Data Assimilation

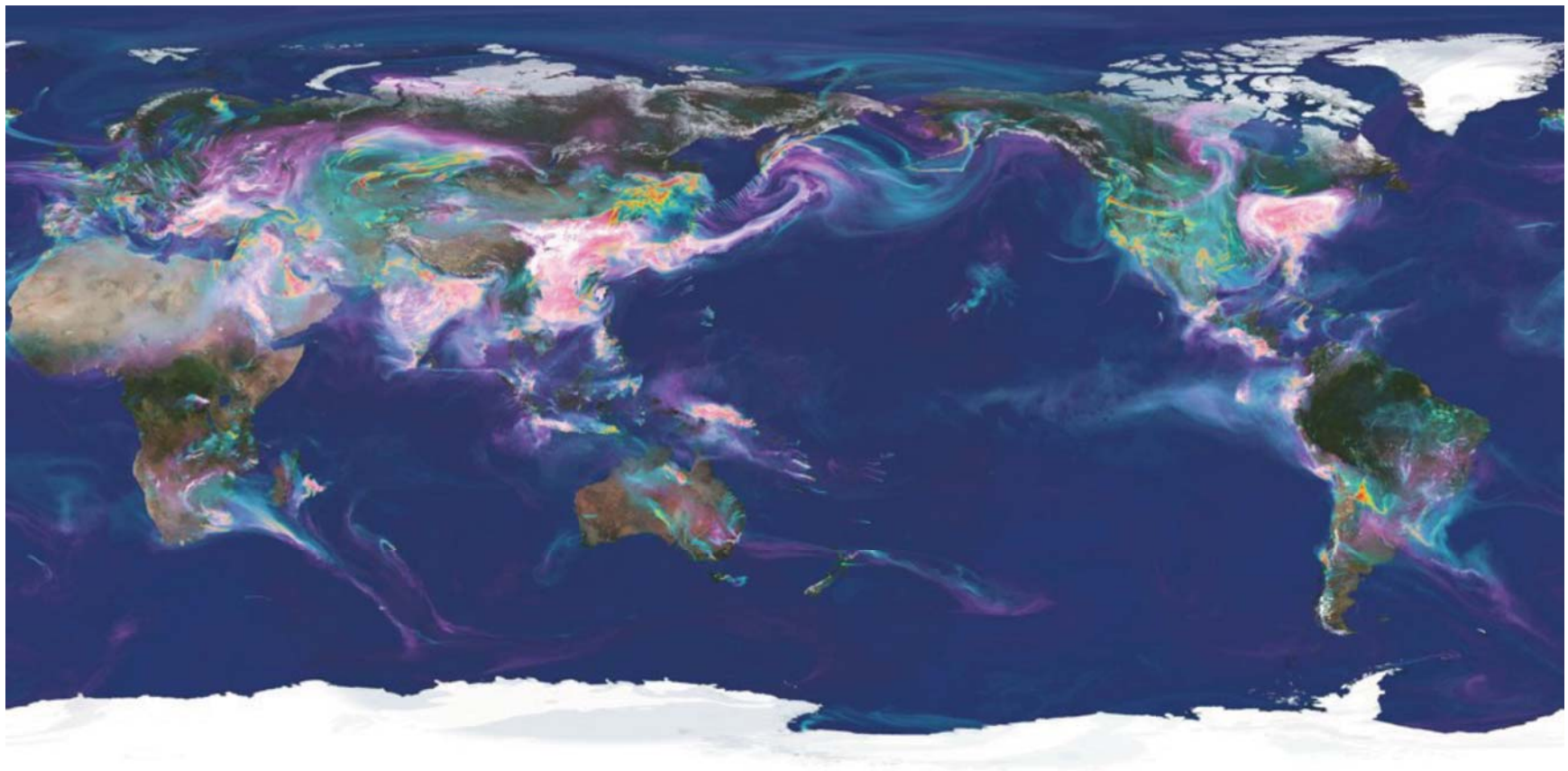


2014 NRT GEOS-5 Model Configuration



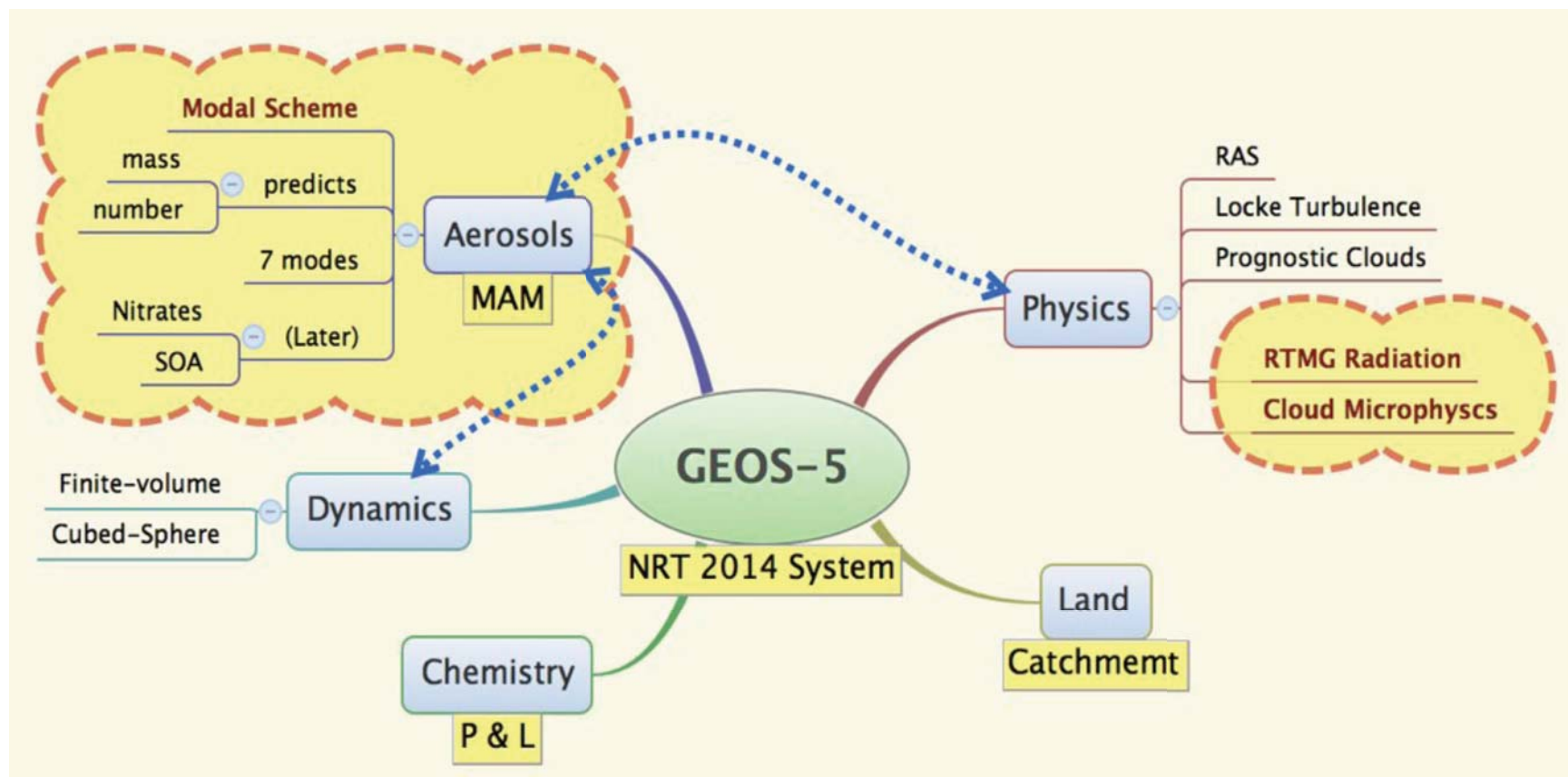
Global, 25 km, 72 Levels, top at 0.01 hPa

GEOS-5 SO₂ & Sulfates



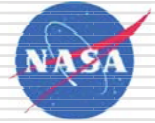
Non-hydrostatic 7km global meso-scale simulation

2015 NRT GEOS-5 Configuration

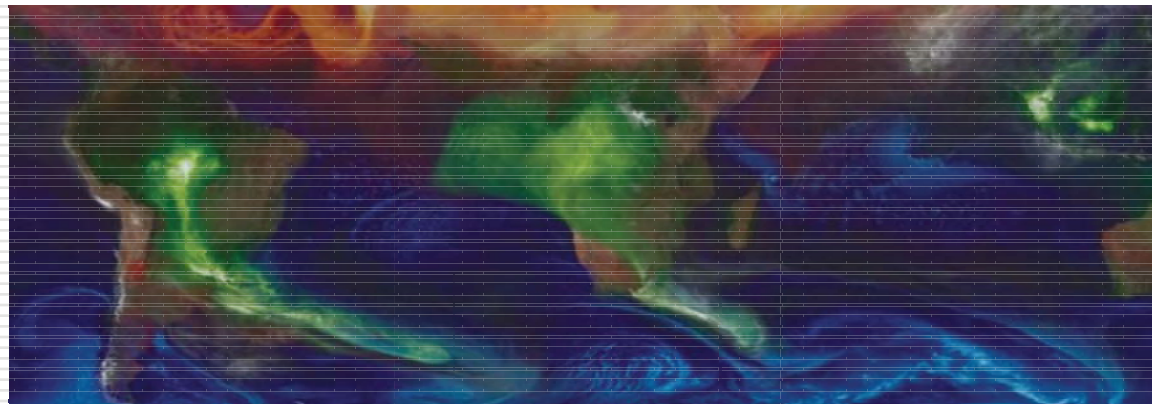


Global, **14 km**, **137** Levels, top at 0.01 hPa

QFED: Quick Fire Emission Dataset

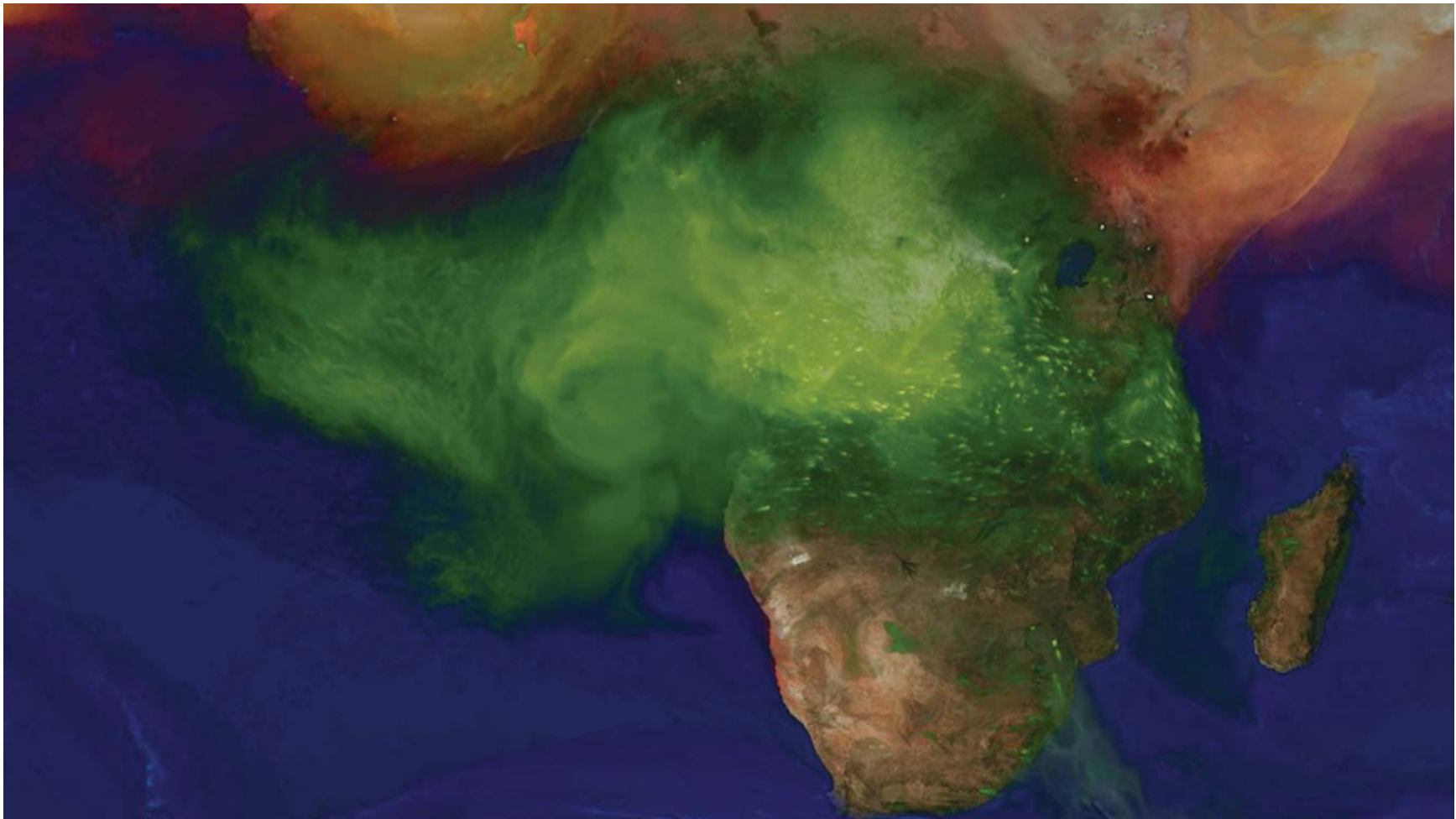


- ❑ Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- ❑ FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data.
- ❑ Daily mean emissions, NRT
- ❑ Prescribed diurnal cycle

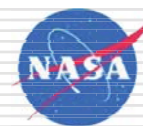


JCSDA: inclusion of geo-stationary information

GEOS-5 Biomass Burning Aerosols



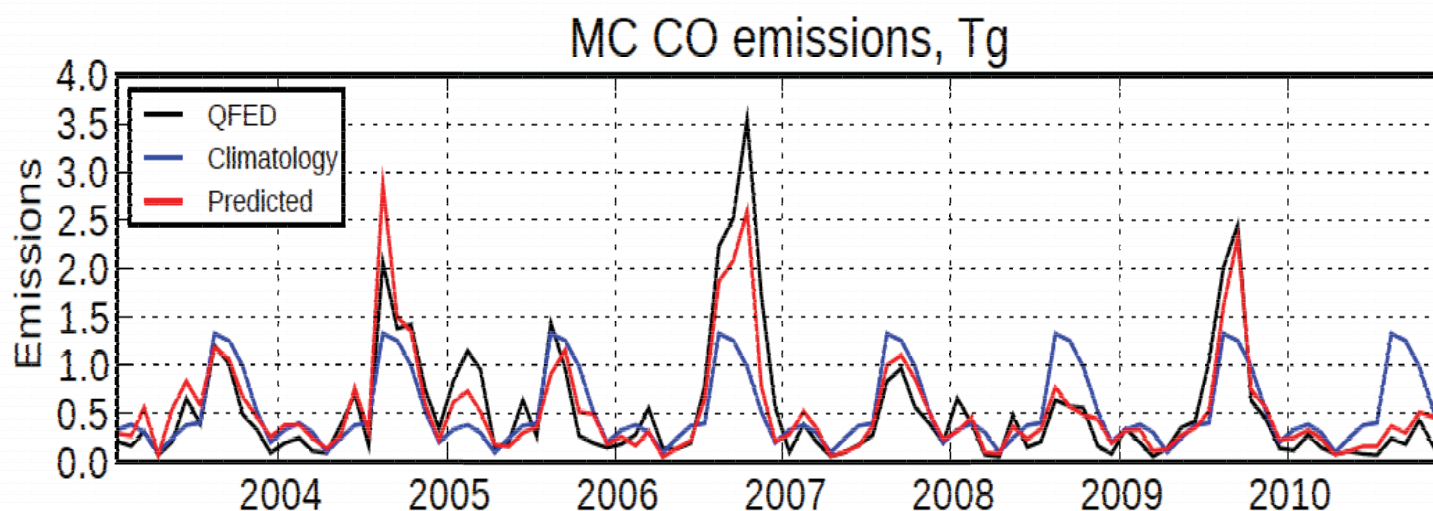
Non-hydrostatic 7km global meso-scale simulation



Modeling Interannual Variability of Biomass Burning Emissions

- BB emission anomalies respond directly to precipitation and surface humidity conditions
- The normalized Canadian Fire Weather Index captures the *fammability* conditions as a function of surface meteorology
- Parameterization:

$$E = \varepsilon \left(\frac{I}{I_{clm}} \right)^{\alpha_b} E_{clm}$$



Maritime Continent Example

Current Status of GEOS-5 Seasonal Prediction

Application

System Characteristics

**Decadal, IPCC
(1960-2009)**

2 deg atmos, 1 deg ocean
MOM4, Fortuna 2.5, specified aerosols (PCHEM), EnOI/SAFE(sea ice) with scout and MERRA forcing; original run in several streams, lost water – sea level problem due to precip correction, new run one stream/no correction

**S-I, NMME
(1979 – present),**

1 deg atmos, ½ ocean, MOM4, Fortuna 2.5, specified aerosols (PCHEM), EnOI, EnKF, with MERRA forcing, altimeter assim.

**IESA
(2013/14)**

¼ deg atmos, 1/10 deg MOM5, Latest Ganymed, using FAST (EnOI with time lagged estimates of cov)

**Current tuning
coupled model**

2 deg atmos, 1 deg ocean, MOM5, latest Ganymed

**ODAS dev.
Aquarius salinity
analysis**

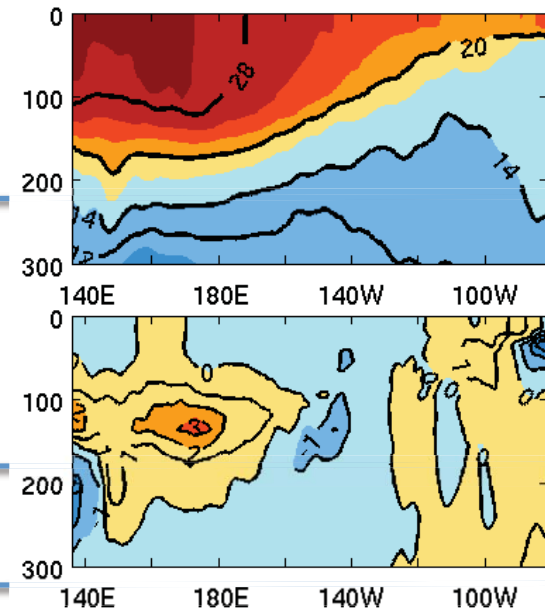
1 deg atmos, 1/2 deg ocean, MOM5, latest Ganymed

Next S-I System

½ deg atmos. Ganymed, ¼ (1/5) MOM5, **interactive aerosols**, new diurnal layer, updated sea ice model, wave model, force with MERRA2, dynamic vegetation, EnOI, Aquarius SSS, new synthetic salinity prior to Argo (2004/5), GRACE ocean mass anomalies, sea level from TOPEX, Poseidon, Jason

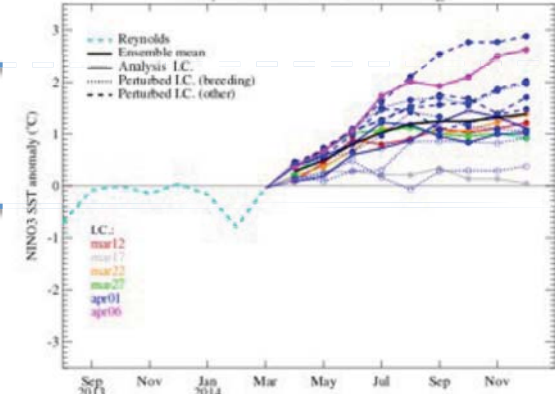
Equatorial Pacific Temperature section and anomaly: AUG2011

ENKF



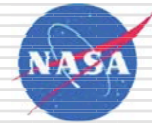
GMAO GEOS-5 Apr 2014 Forecast

Monthly mean anomalies relative to 1981-2010 climatology

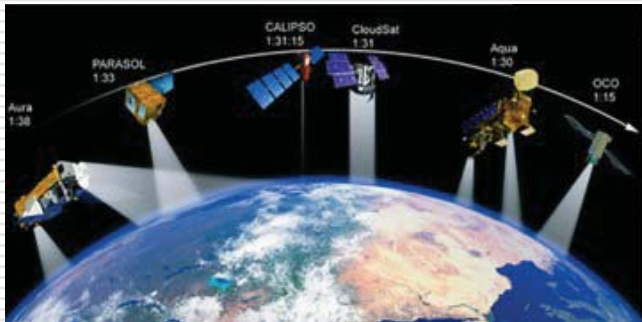


Aerosol Data Assimilation

2014 NRT Configuration



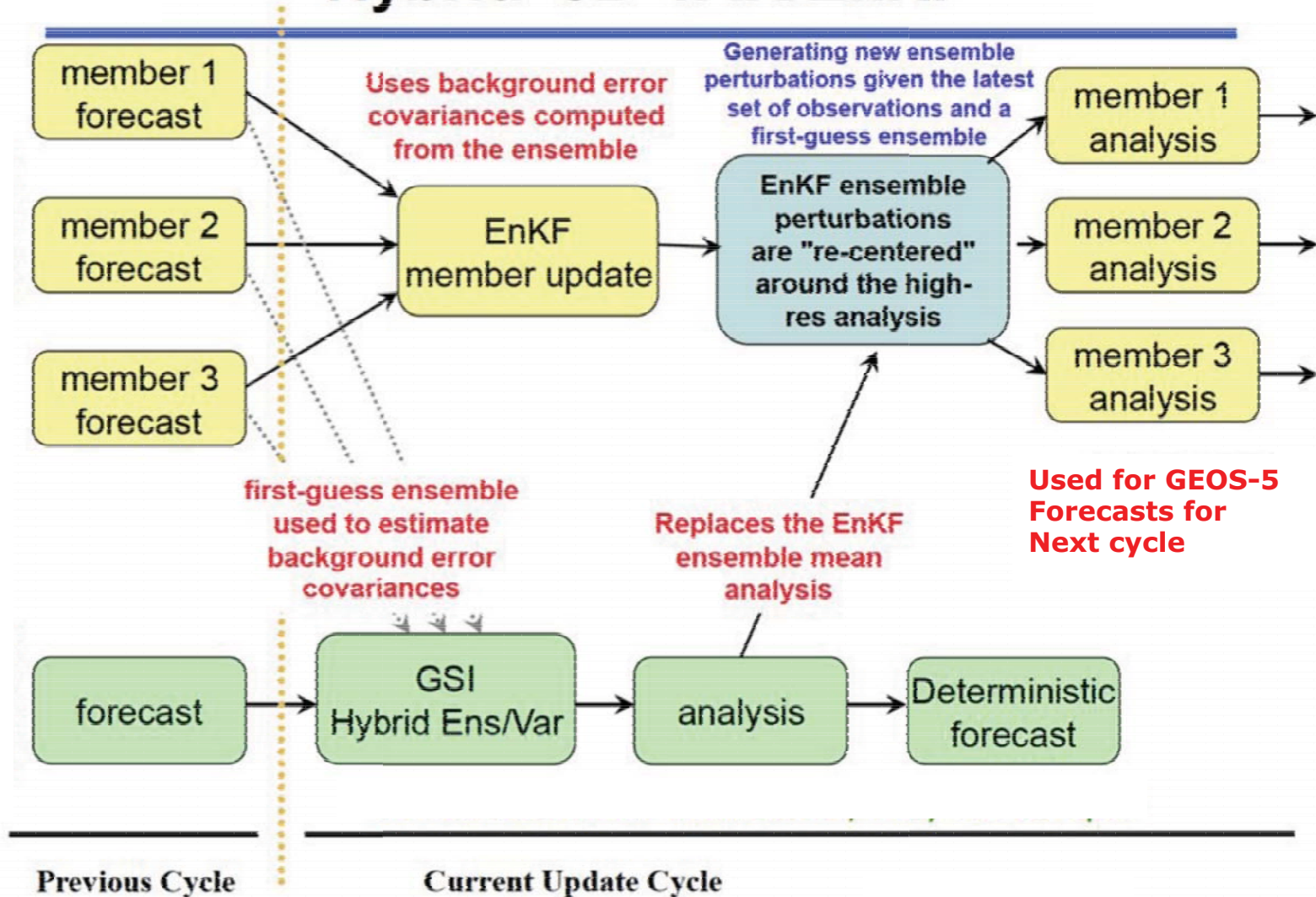
- Focus on NASA EOS instruments, MODIS for now



- Global, high resolution 2D AOD analysis
- 3D increments by means of Local Displacement Ensembles (**LDE**)

- Simultaneous estimates of background bias (*Dee and da Silva 1998*)
- Adaptive Statistical Quality Control (*Dee et al. 1999*):
 - State dependent (adapts to the error of the day)
 - Background and Buddy checks based on log-transformed AOD *innovation*
- Error covariance models (*Dee and da Silva 1999*):
 - Innovation based
 - Maximum likelihood

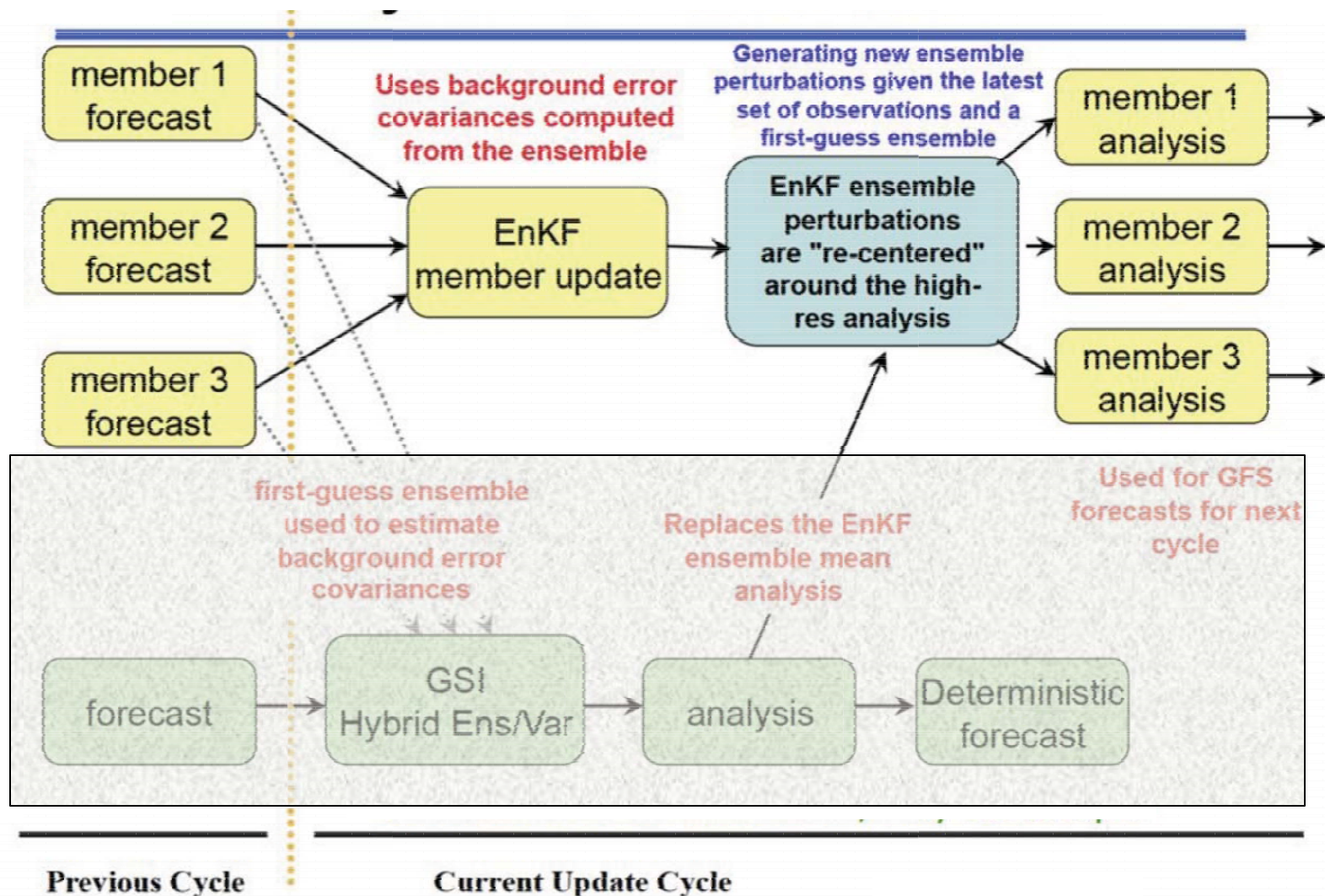
Hybrid 3D-VAR/EnKF

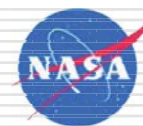


In collaboration with NOAA NCEP, ESRL

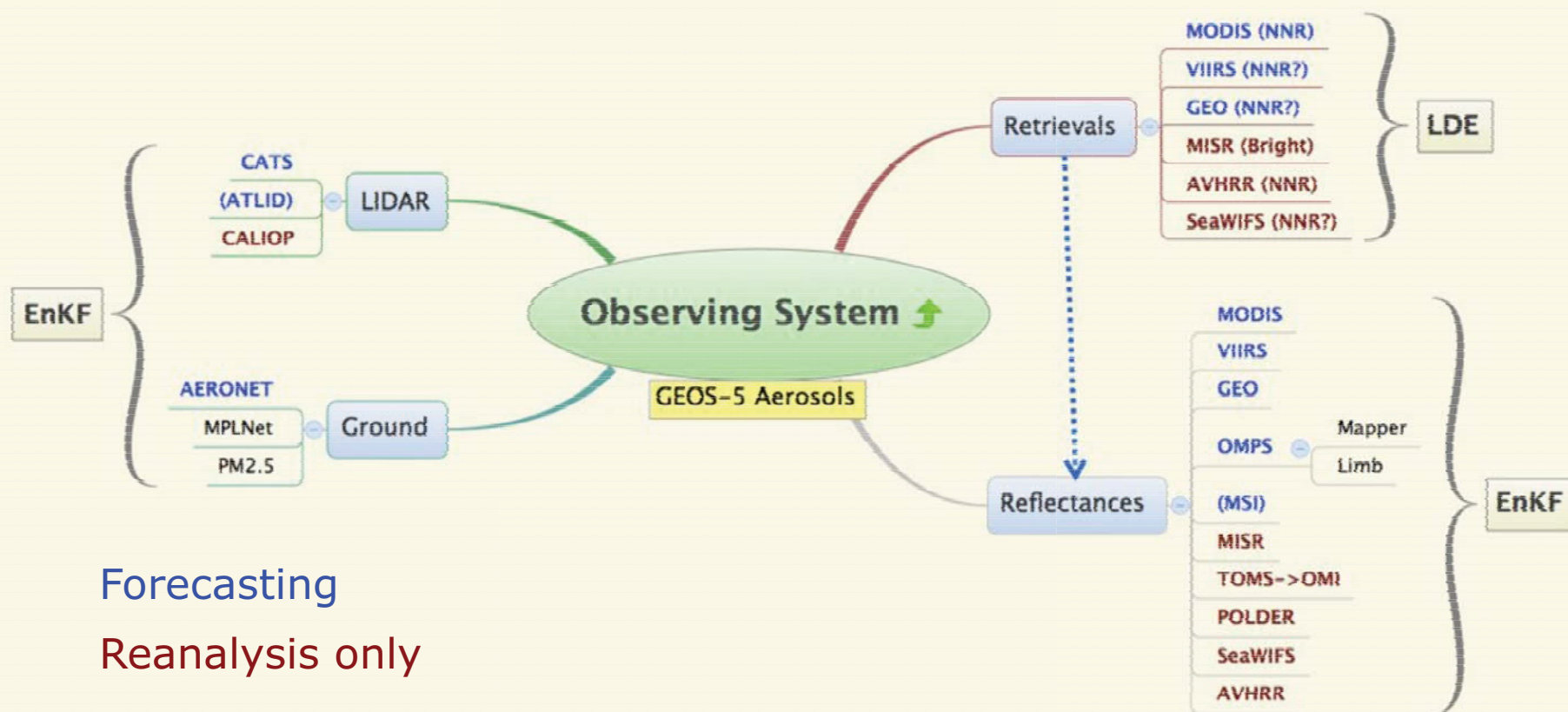
GEOS-5 **Aerosol** Assimilation

Phase I: EnKF Only





Aerosol Observing System



Aerosol Data Assimilation in GEOS-5

Outline

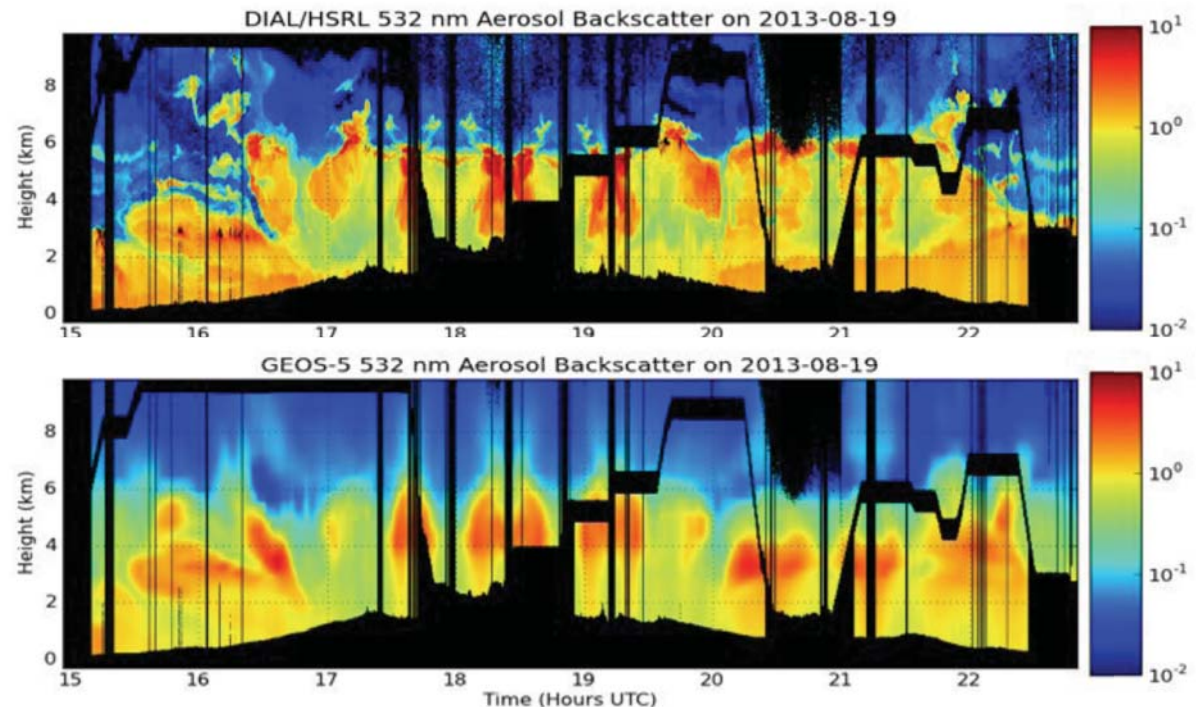


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Field Campaign Support



- Global 5-day chemical forecasts
 - O₃, aerosols, CO, CO₂, SO₂
 - Nominally 25 km
- Driven by real-time biomass emissions from MODIS FRP (QFED)
- Constituents transported on-line, interactively
- Since 2007 supported several field missions including TC₄, ARCTAS, GloPac, ATTREX, DISCOVER-AQ, HS₃, SEAC₄RS, etc.



Comparison of observed (top) and simulated (bottom) aerosol backscatter for a slight during the 2013 SEAC₄RS campaign.

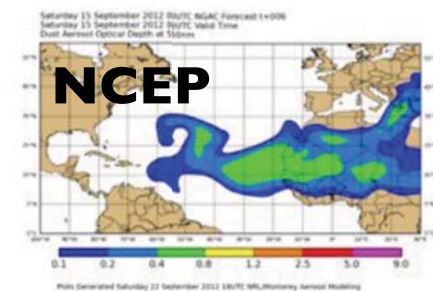
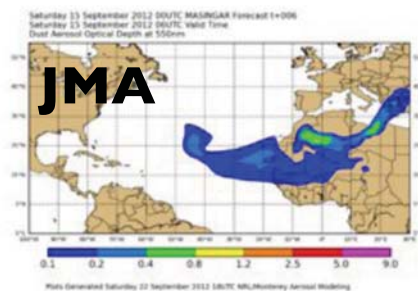
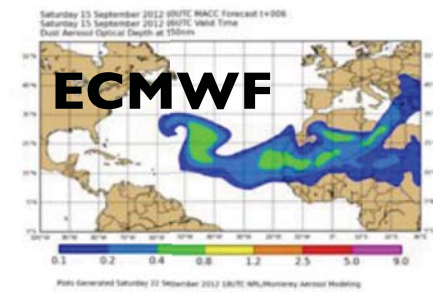
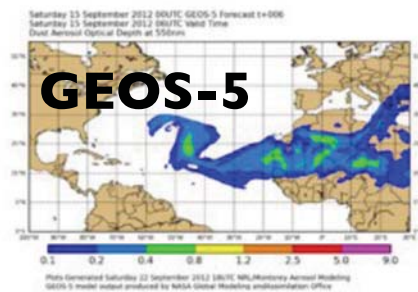
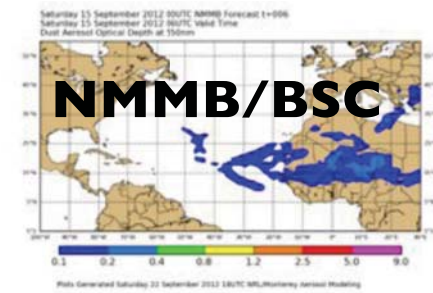
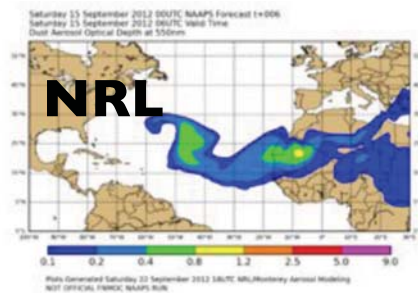
<http://gmao.gsfc.nasa.gov/forecasts/>



International Cooperative for Aerosol Prediction (ICAP)



ICAP is an international forum for aerosol forecast centers, remote sensing data providers, and lead systems developers to share best practices and discuss pressing issues facing the operational aerosol community.



GEOS-5 Reanalysis Activities

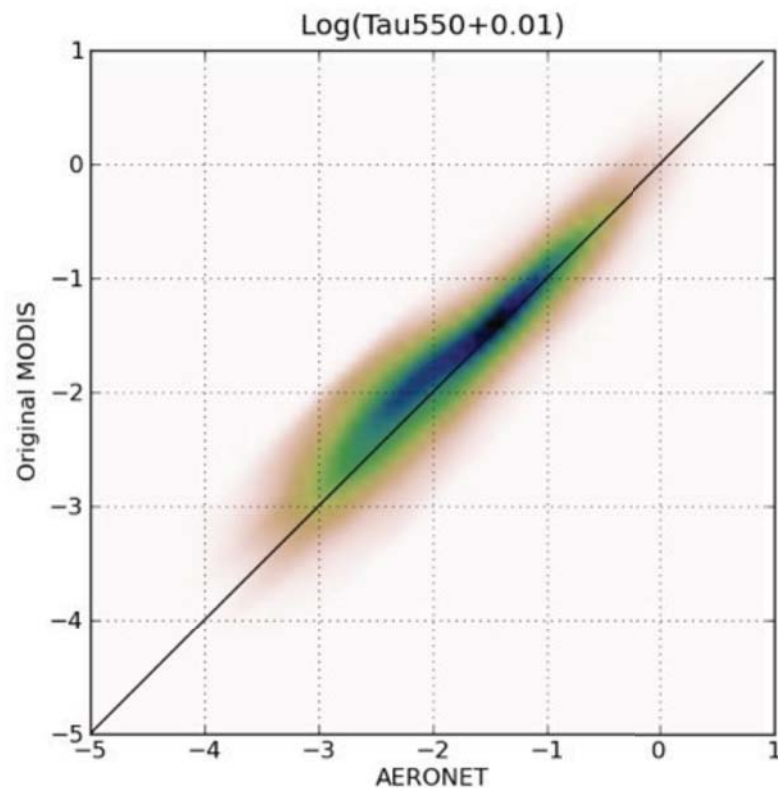


Name	Nominal Resolution	Period	Aerosol Data	Available
MERRA-1	50 km	1979-present	NONE	now
MERRAero	50 km	2002-present	MODIS C5	now
FP for Inst. Teams	50 km	1997-	MODIS C5	In progress
NCA	25 km	2010-11	MODIS C5, MISR	Now
MERRA-2	50 km	1979-present	AVHRR, MODIS C5, MISR, AERONET	Q1 2015

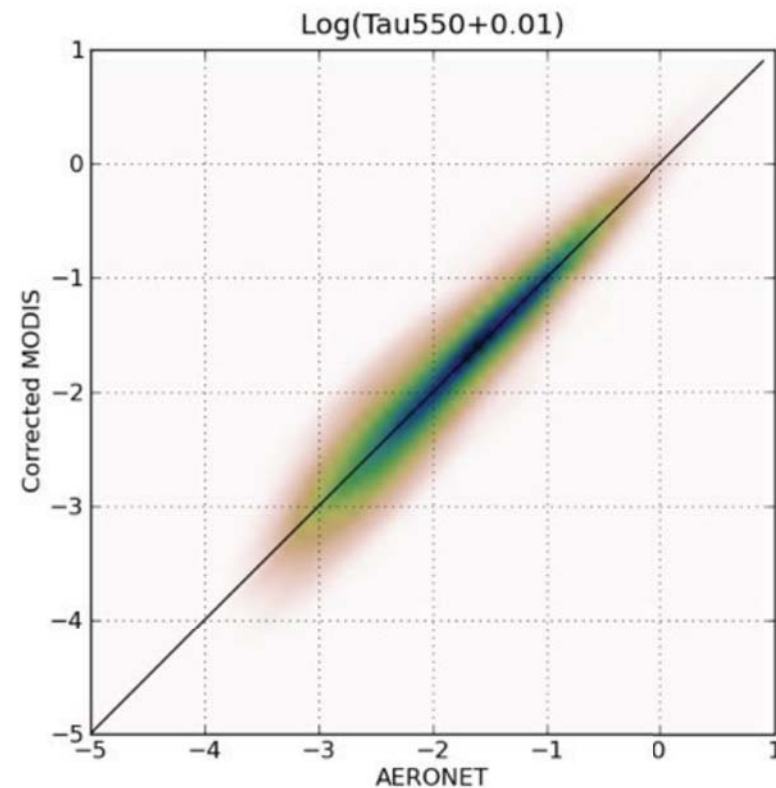
Observational Bias



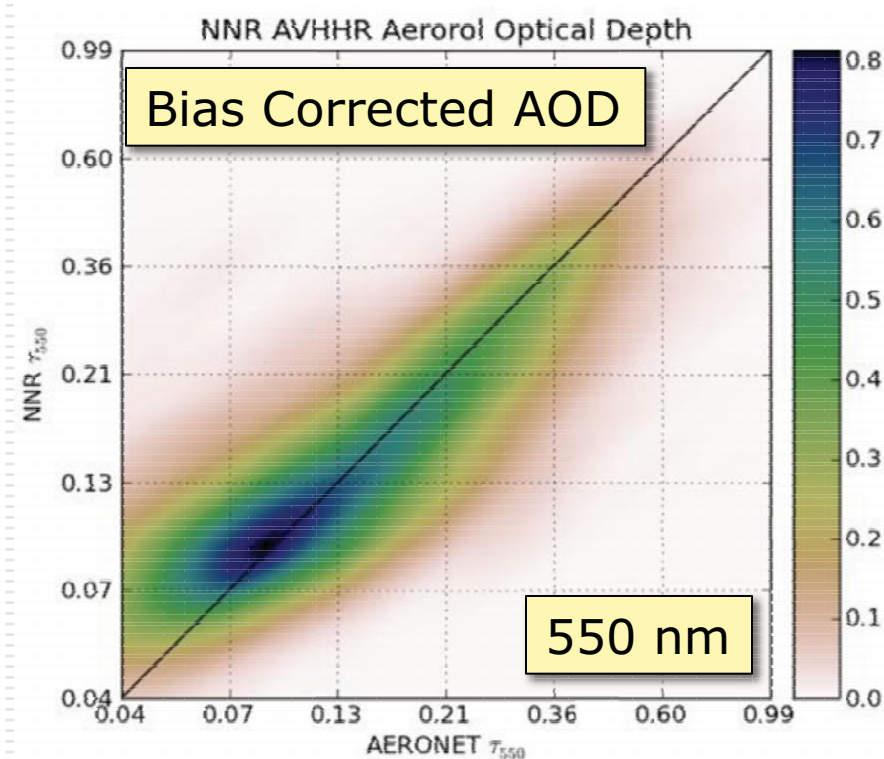
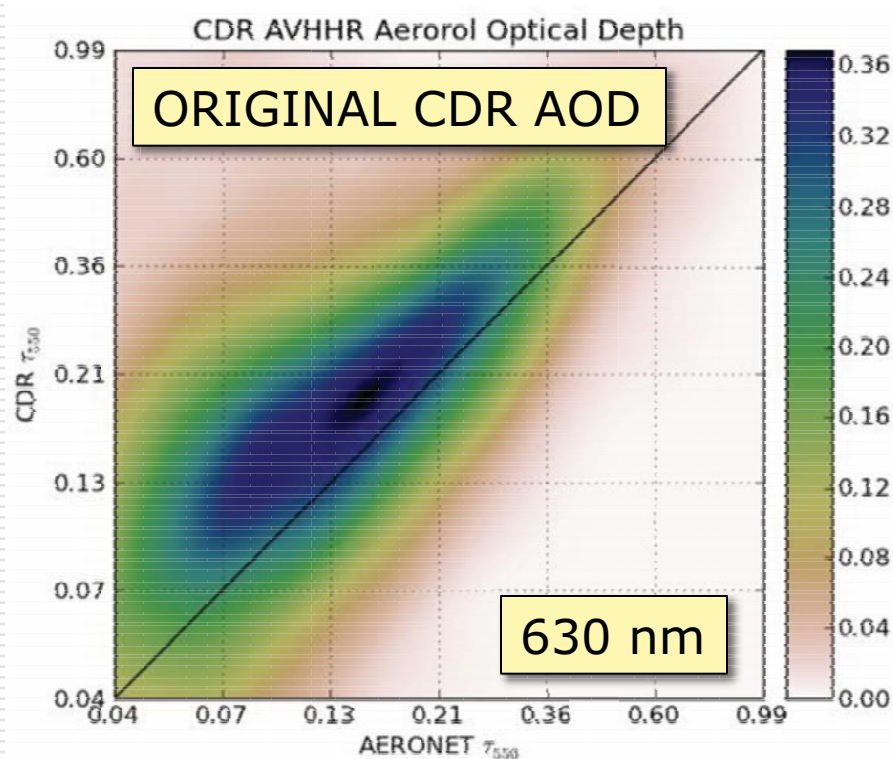
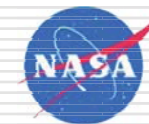
ORIGINAL MODIS AOD



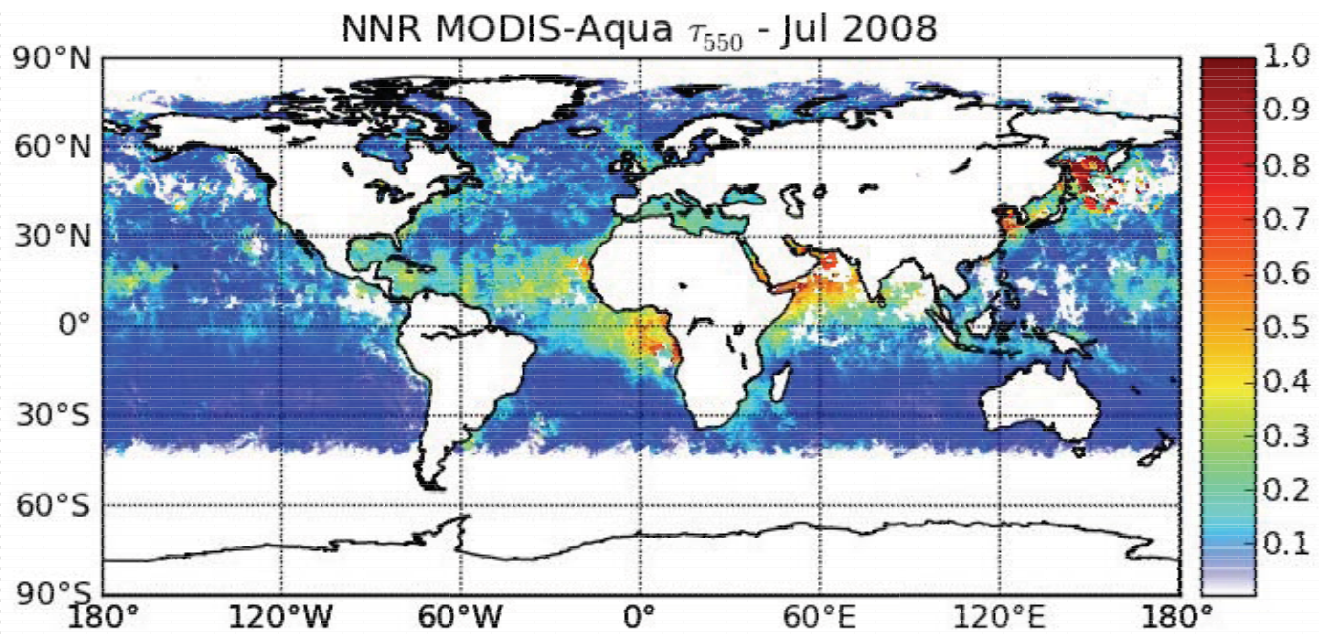
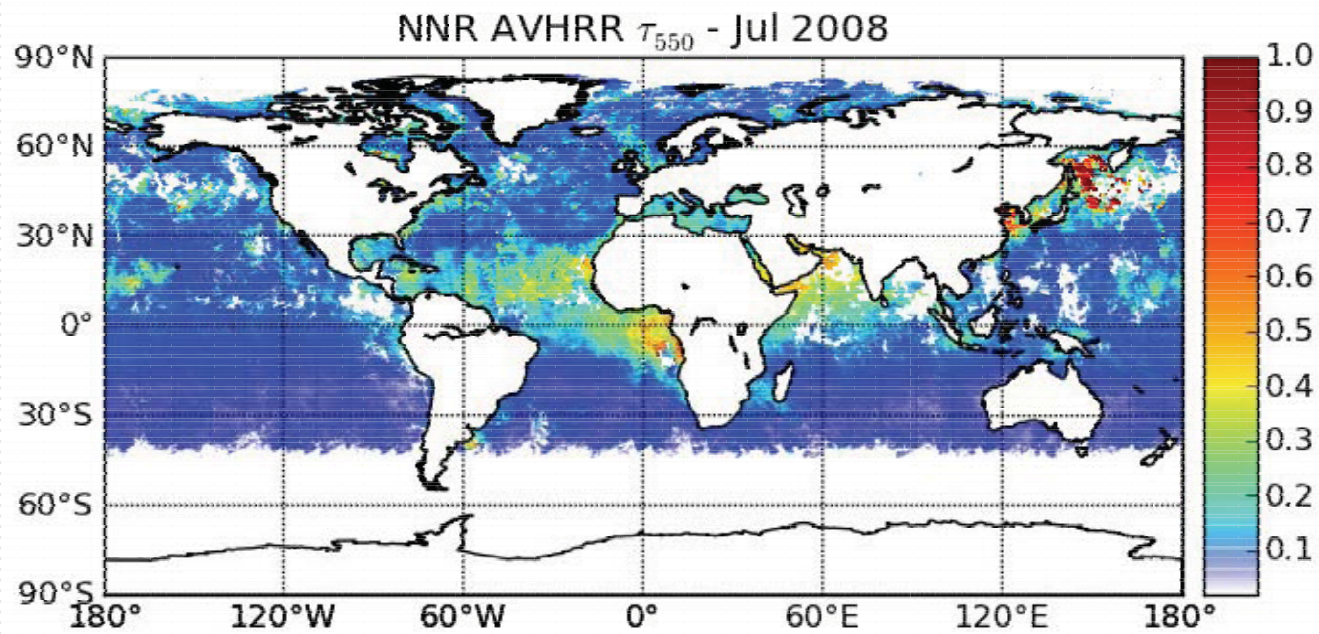
BIAS CORRECTED AOD



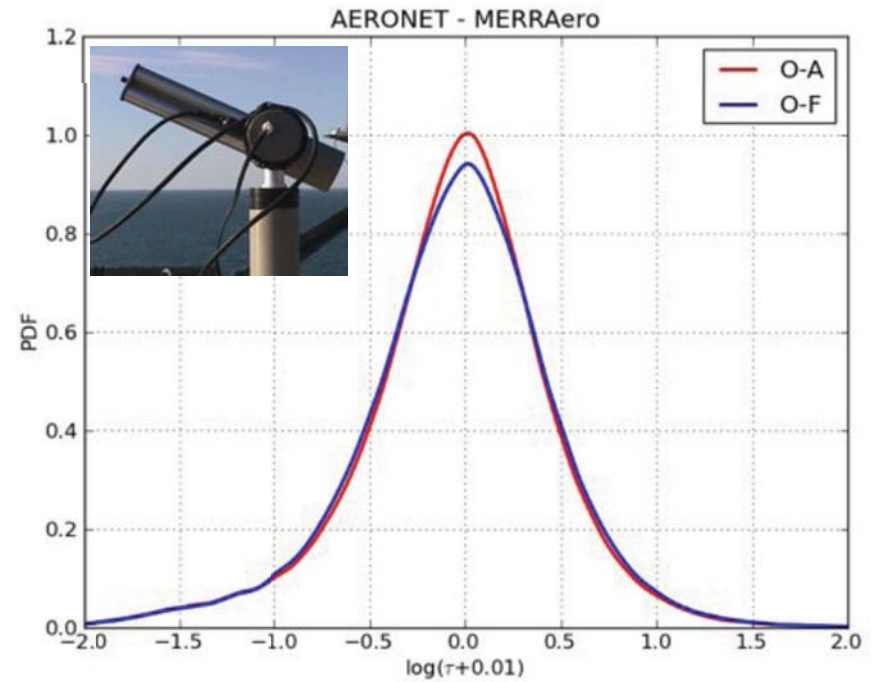
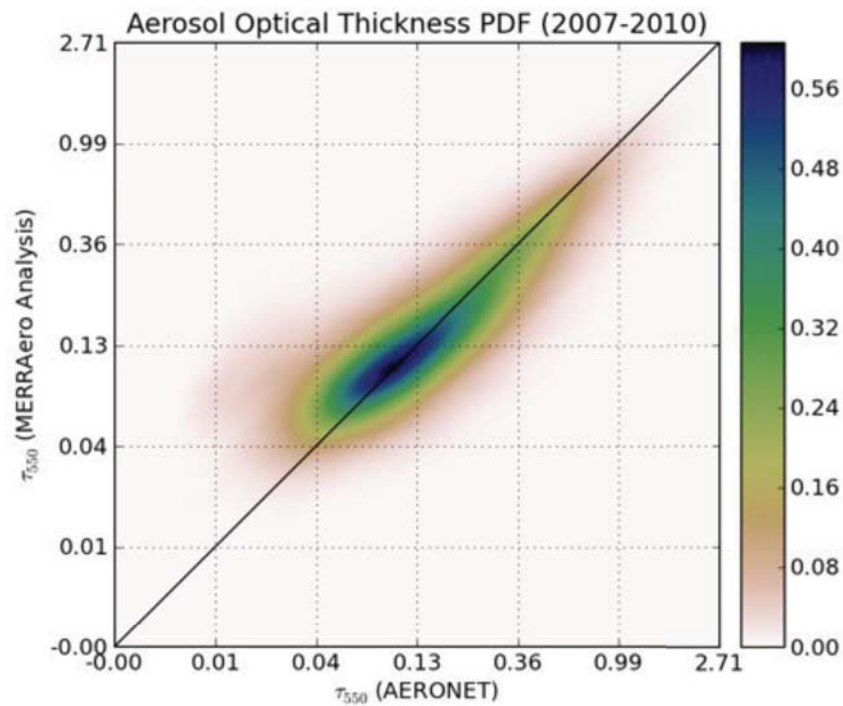
AVHRR NOAA CDR AOD *AERONET Comparison*



Coastal and Island Stations for 2003-2009

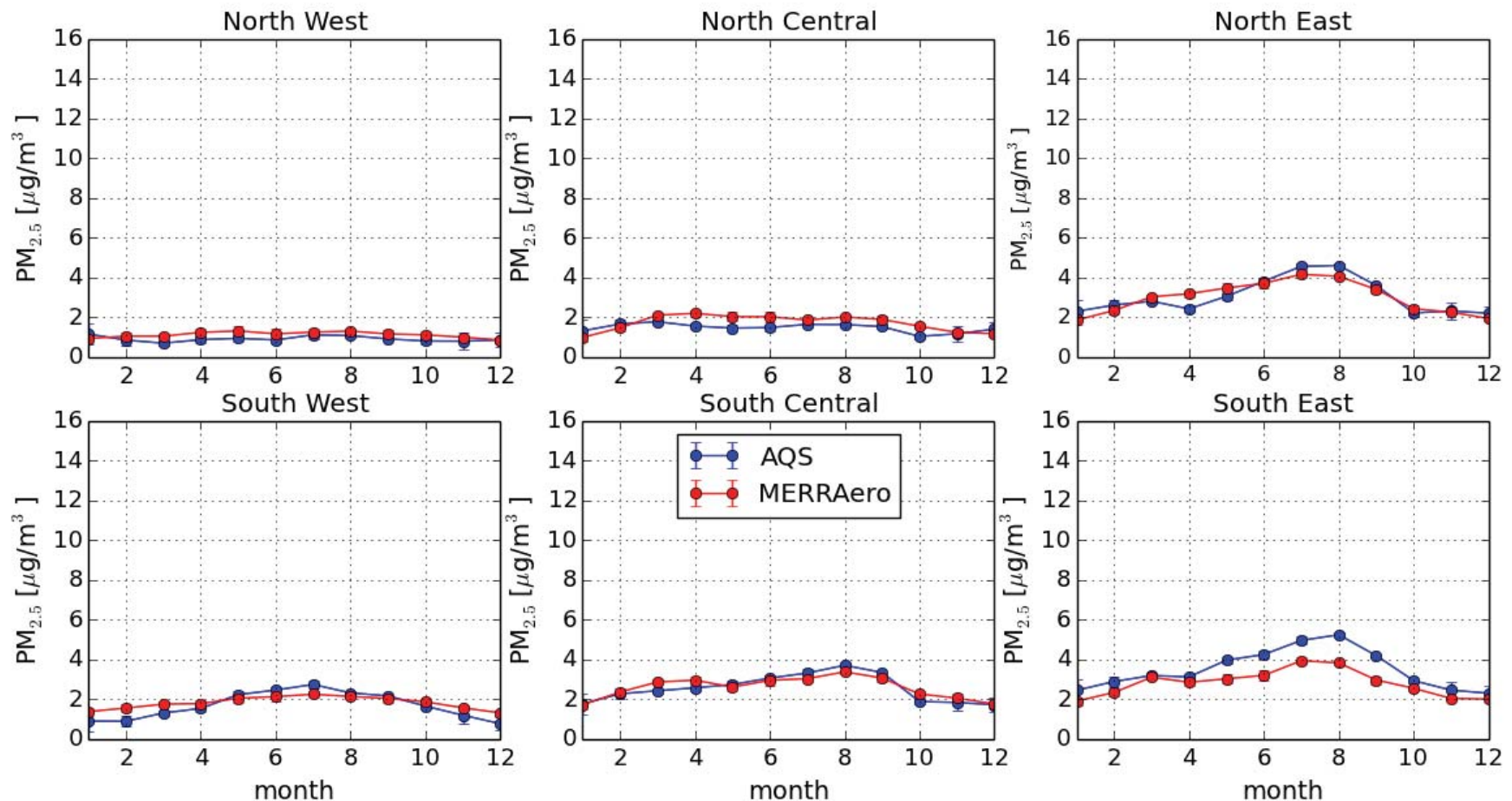


AERONET MERRAero Validation

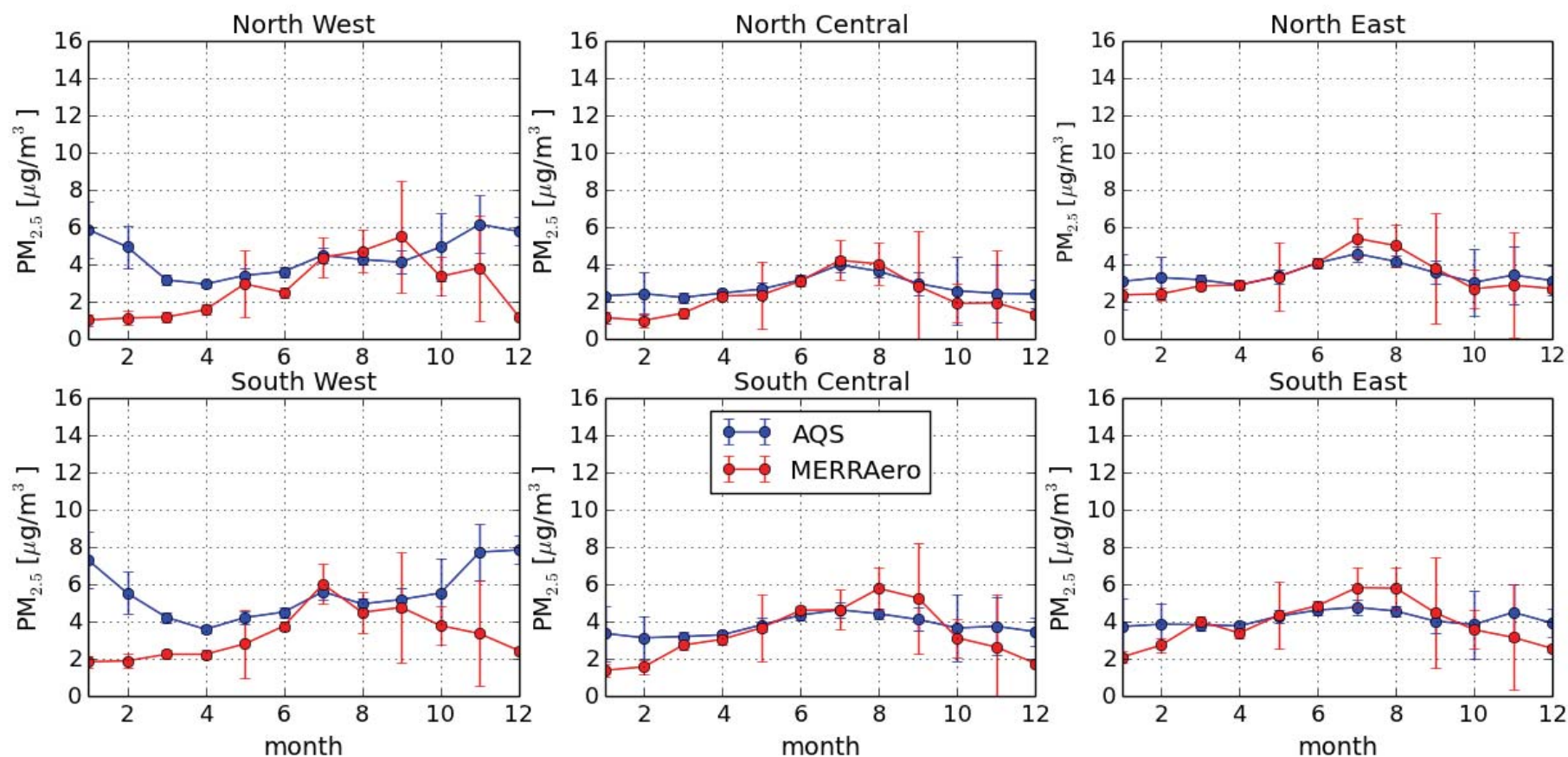


$$\eta = \log(\tau + 0.01)$$

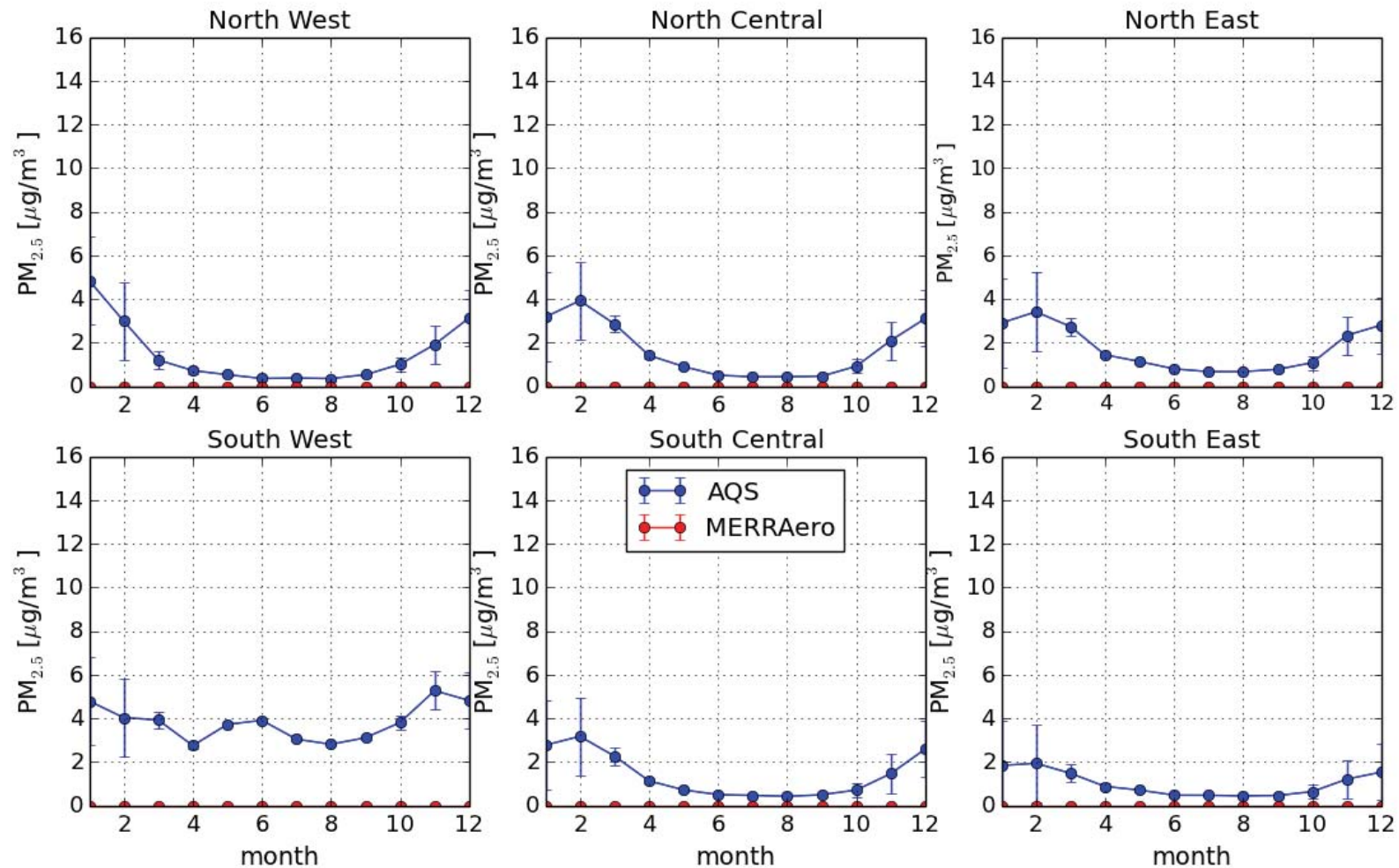
PM_{2.5} (Sulfates) Regional Climatology



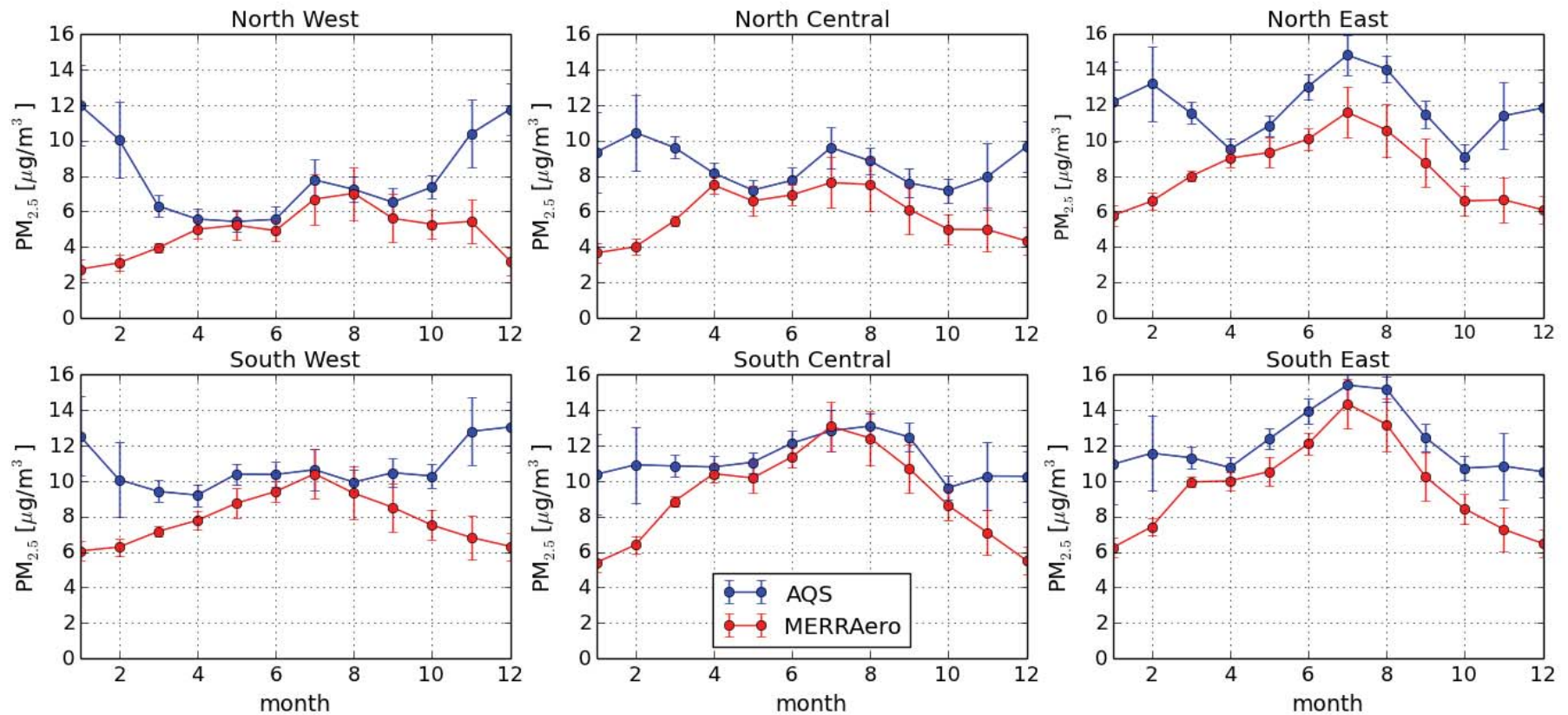
PM_{2.5} (Organic Carbon) Regional Climatology



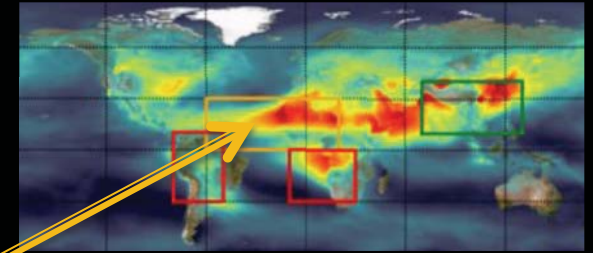
PM_{2.5} (Nitrates) Regional Climatology



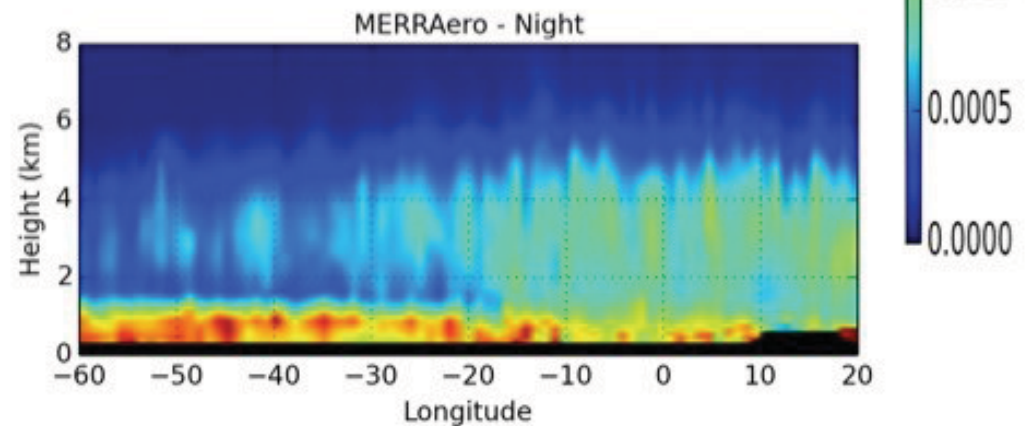
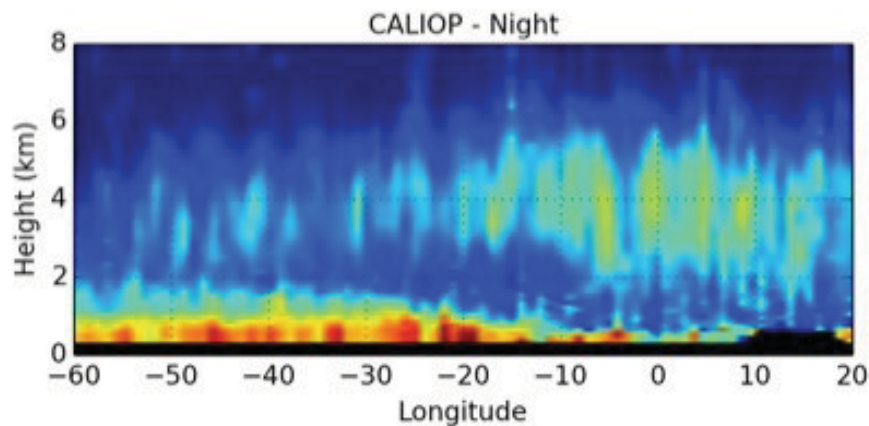
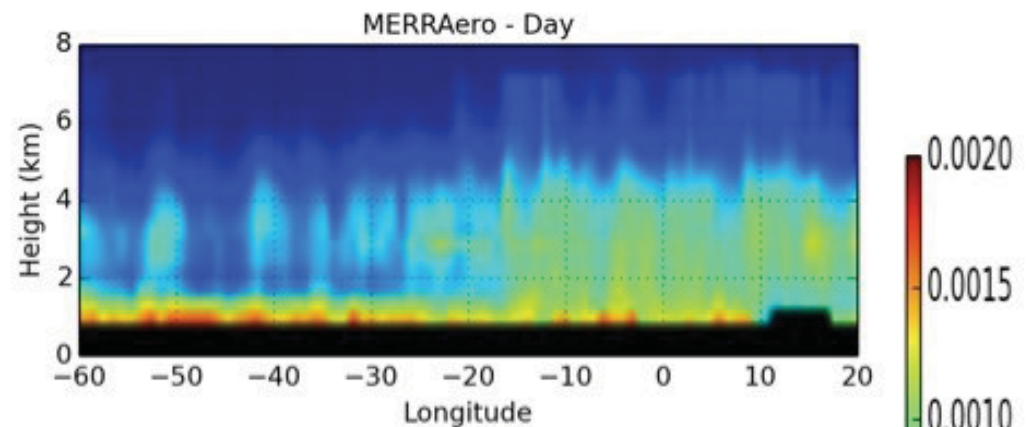
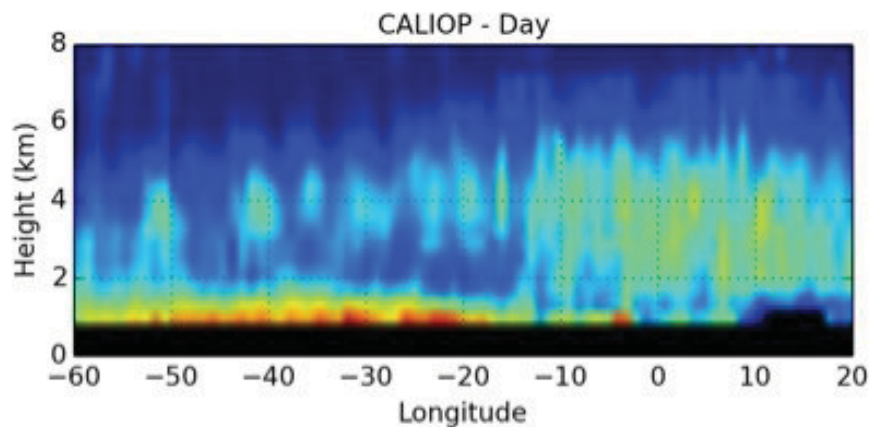
PM_{2.5} (Total) Regional Climatology



Vertical Structure: Comparison to CALIOP



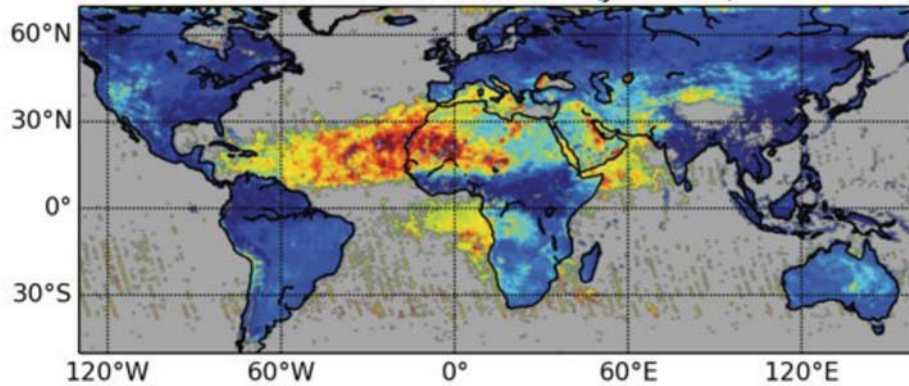
DUST



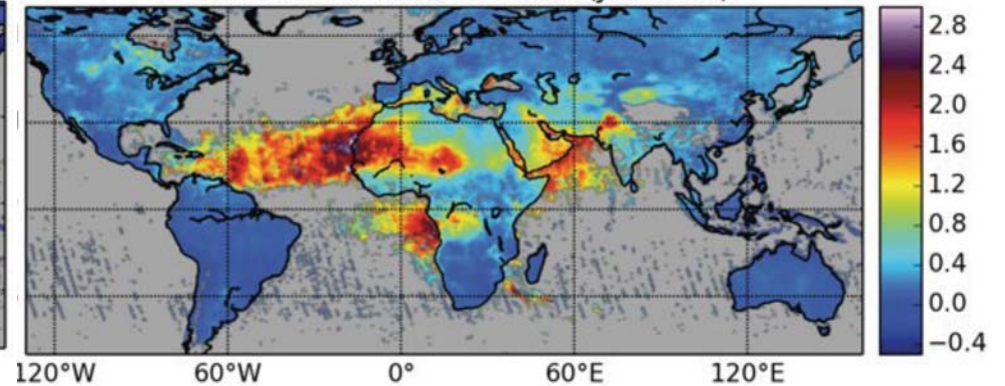
Evaluation of MERRAero Absorption using OMI



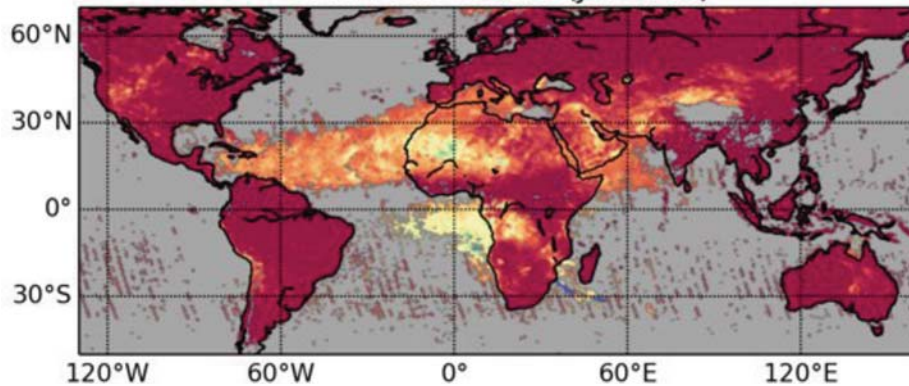
OMI UV Aerosol Index (Jul 2007)



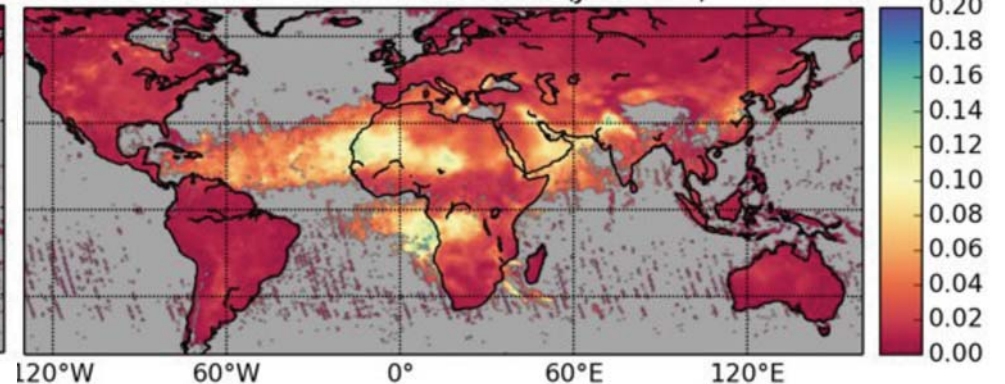
MERRAero UV Aerosol Index (Jul 2007)



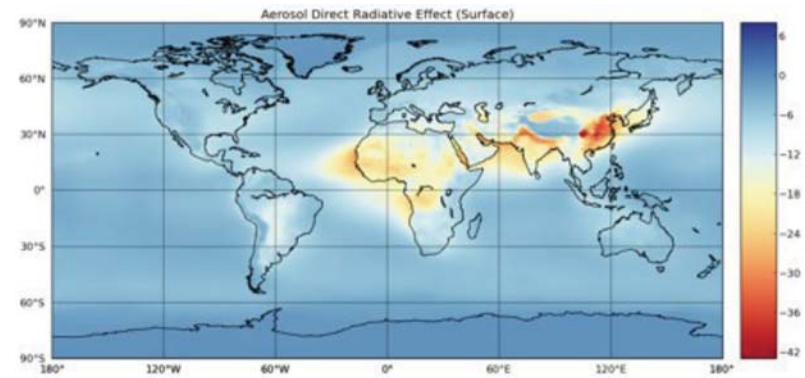
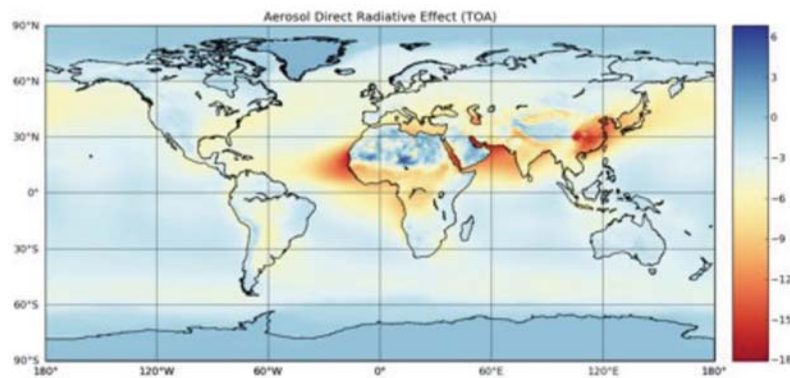
OMI AAOD 388nm (Jul 2007)



MERRAero AAOD 388 nm (Jul 2007)



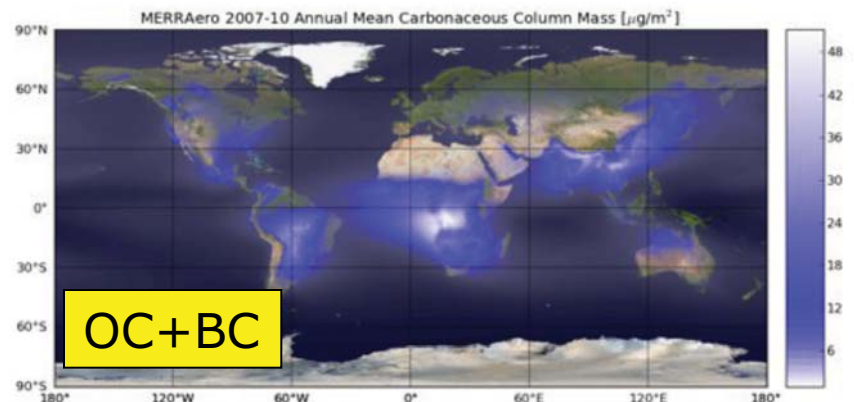
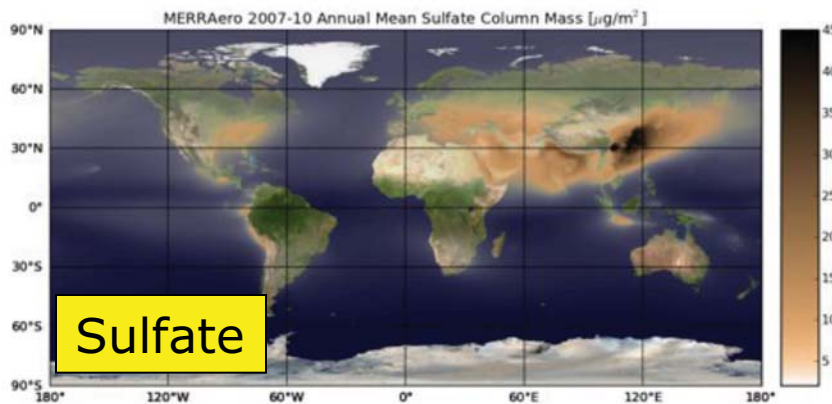
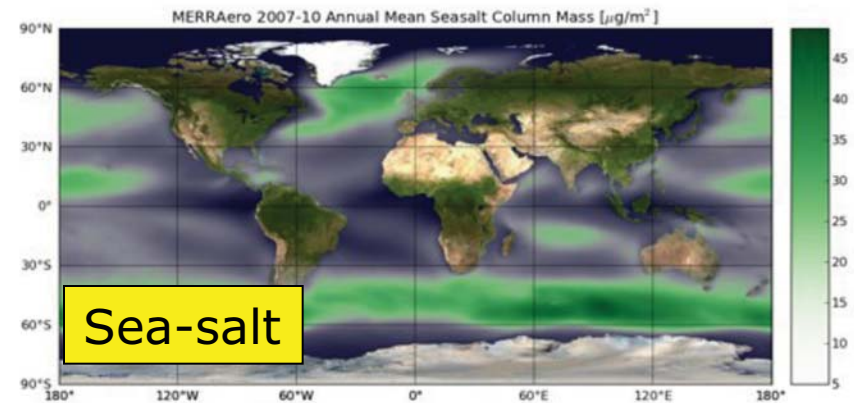
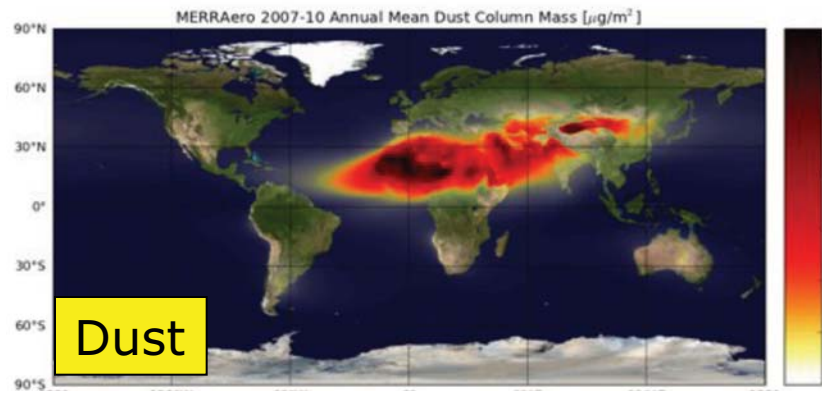
Clear-Sky Aerosol Direct Radiative Effect



Source	TOA SW DRE Ocean (Land)		Atmos. Ocean (Land)		Surface SW DRE Ocean (Land)	
MERRAero	-3.8	(-4.3)	2.8 (6.8)		-6.6	(-11.1)
Other Observational Yu <i>et al.</i> (2006)	-5.5 ± 0.2 (-4.9 ± 0.7)		3.3 (6.8)		-8.8 ± 0.7 (-11.8 ± 1.9)	
Multi-model Ensemble Yu <i>et al.</i> (2006)	-3.4 ± 0.6 (-2.8 ± 0.6)		1.4 (4.4)		-4.8 ± 0.8 (-7.2 ± 0.9)	
GEOS-5 (Free)	-3.4	(-2.7)	0.5 (2.8)		-3.9	(-5.5)

$$DRE_{SW} = \left(F_{SW}^{\downarrow} - F_{SW}^{\uparrow} \right)_{Aerosols} - \left(F_{SW}^{\downarrow} - F_{SW}^{\uparrow} \right)_{NoAerosols}$$

Assimilated Aerosol Annual Mean Mass



Speciation potentially adjusted by spectral reflectances

Mass Budget



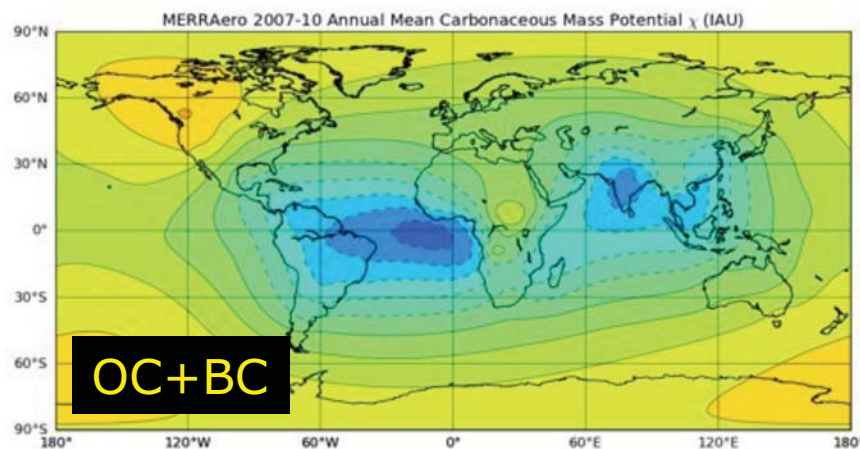
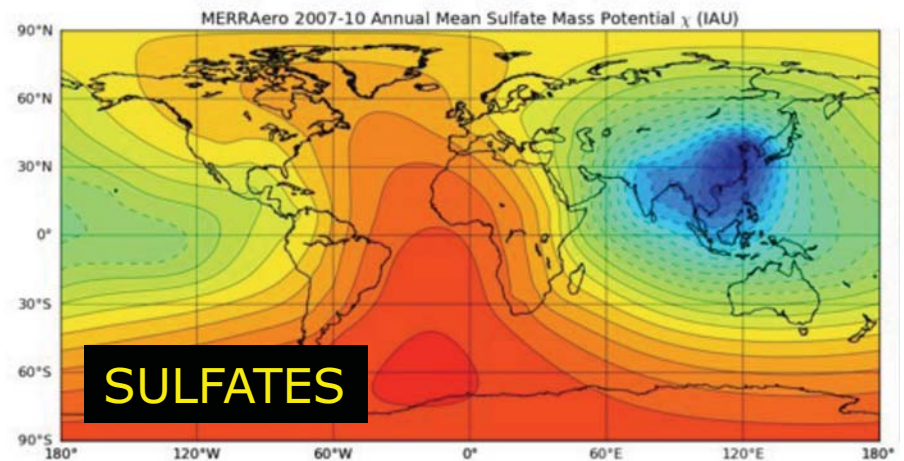
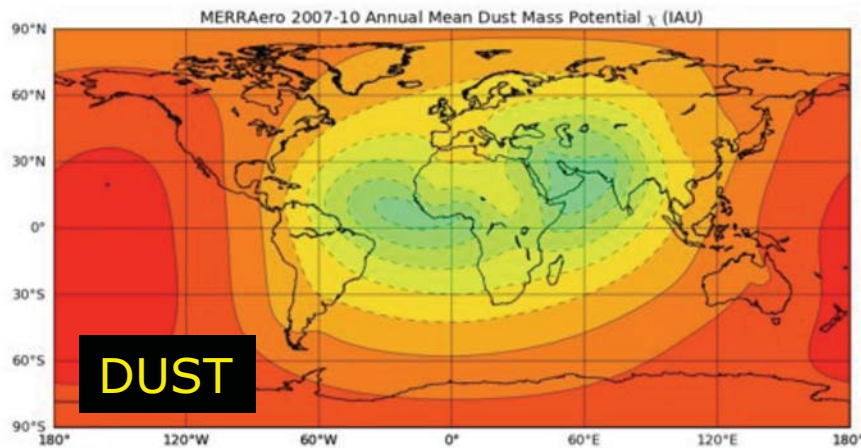
Annual mass budget for an aerosol specie q :

$$\nabla \cdot \overline{\langle \mathbf{u}q \rangle} = \overline{E} + \overline{P} - \overline{L} + \frac{\overline{\langle \Delta q^a \rangle}}{\tau}$$

where

$\mathbf{u}q$	Mass flux
E	Emissions
P	Chemical production
L	Loss processes
Δq^a	Analysis increments
τ	Analysis interval (3 hours)
$\langle \cdot \rangle$	Mass weighted vertical integral
$\overline{(\cdot)}$	Time average

Annual Mean Analysis Increments



$$\chi = \nabla^{-2} \left[(\bar{E} + \bar{P} - \bar{L} + \frac{\langle \Delta q^a \rangle}{\tau}) \right]$$

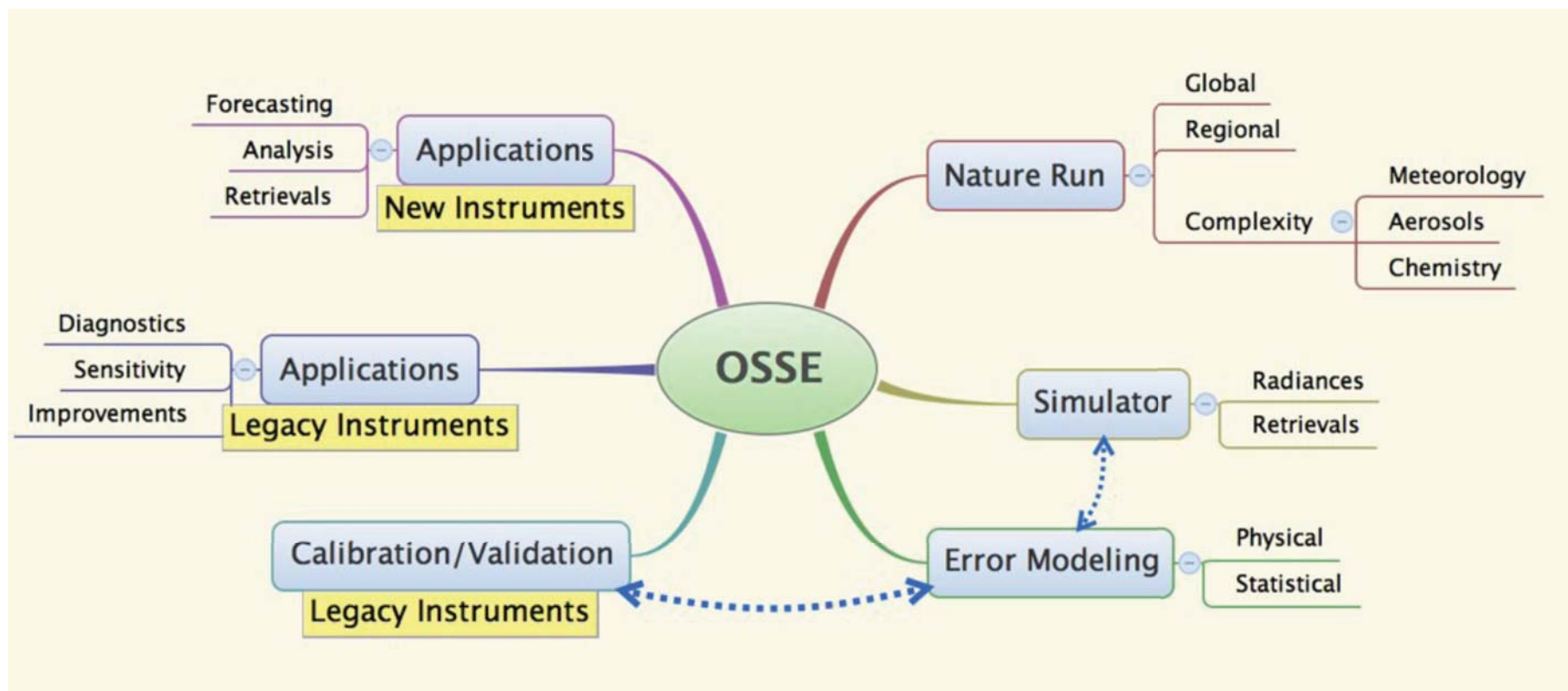
- Observing System
- Simulation
- Experiment

Model-based OSSE

A framework for numerical experimentation in which *observables* are simulated from fields generated by an earth system model, including a *parameterized* description of the *observational error* characteristics.

Simulations are performed in support of an experimental goal.

Elements of an OSSE System

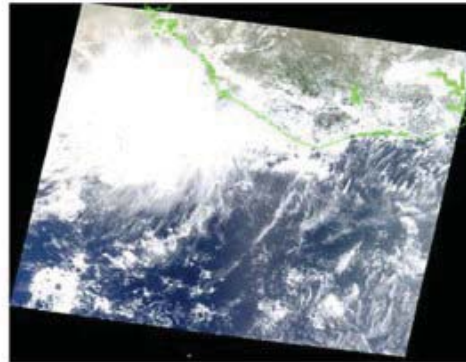


MODIS Cloud & Aerosol Retrieval Simulator

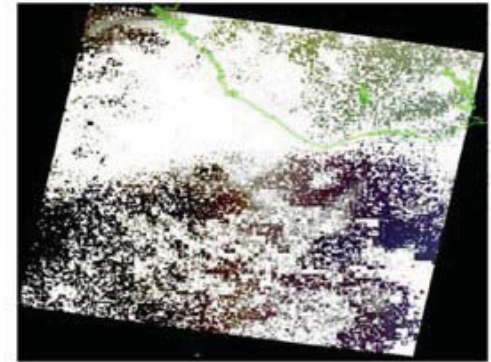


- PDF based **sub-grid sampling** of GEOS-5 fields (ICA)
- Spatial “clumping”
- Radiances for 27 MODIS channels
- Cloud and aerosol extinction, ssa, phase function
- Operational Retrievals
 - Clouds: **MOD06**
 - Aerosols: **MOD04**

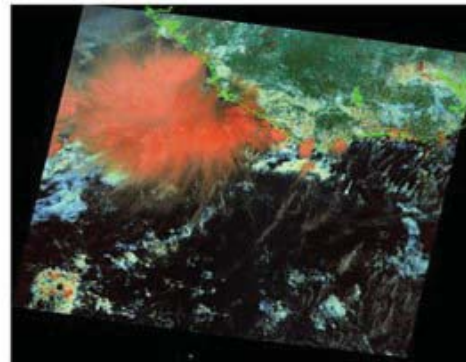
a) Actual RGB composite



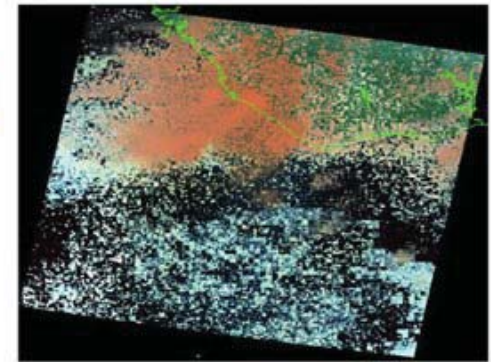
b) Simulated RGB composite



c) Actual SWIR composite



d) Simulated SWIR composite

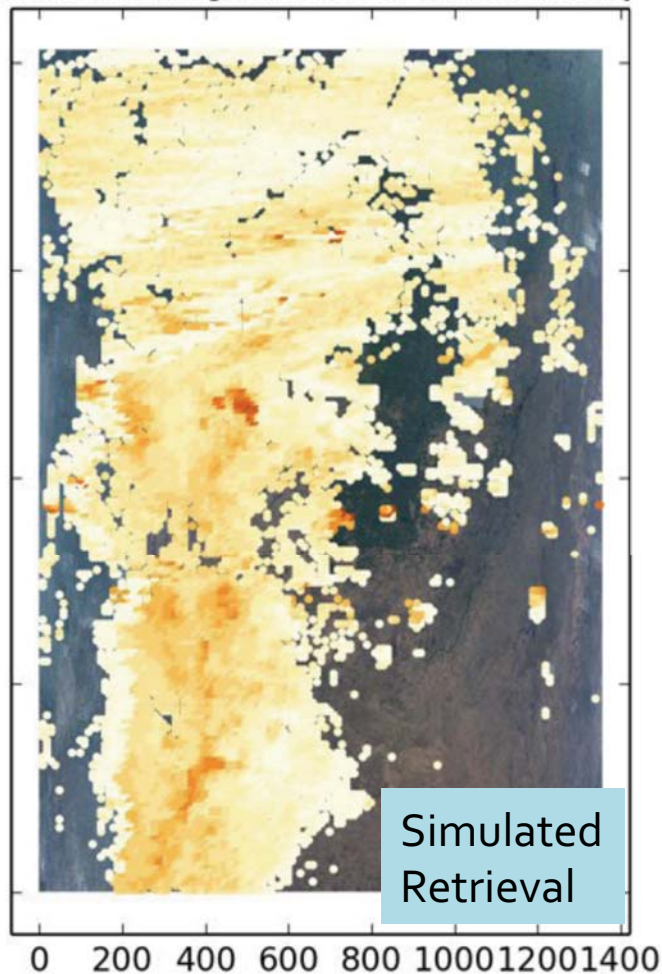


Wind et al., 2013, GMD

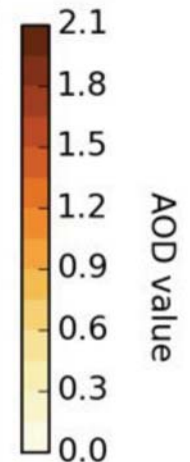
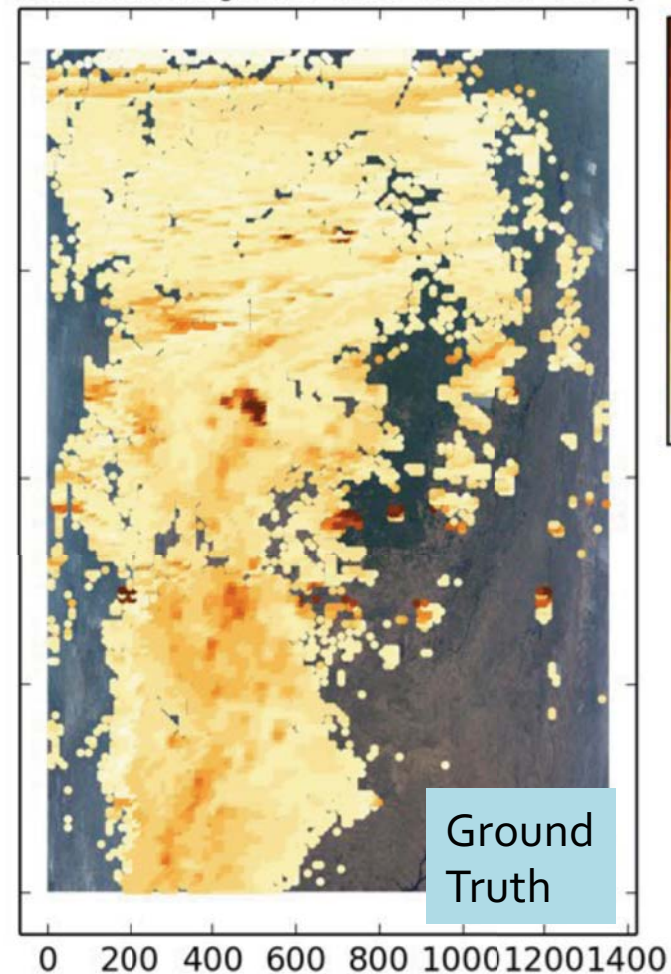
MODIS Retrieval Simulator Biomass Burning in Brazil



Modis RGB Image with MYD04 retrieval overlay



Modis RGB Image with GEOS-5 aerosol overlay

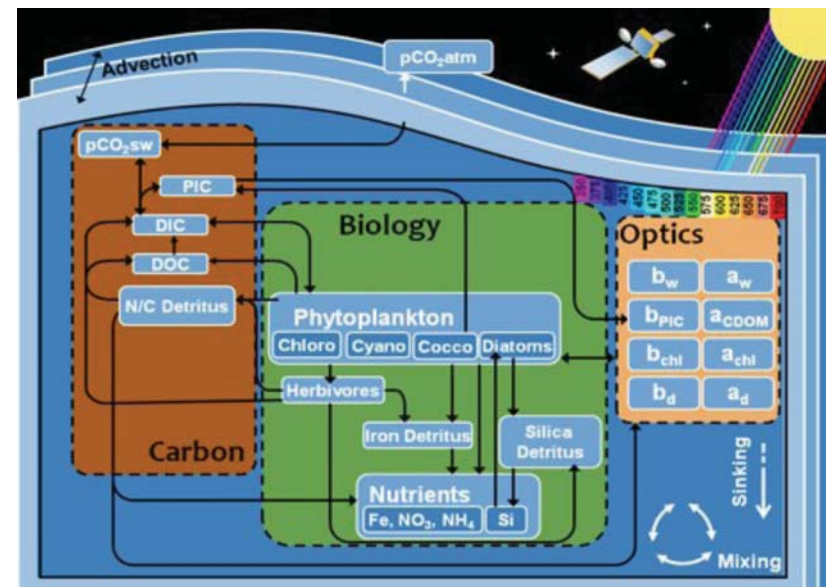
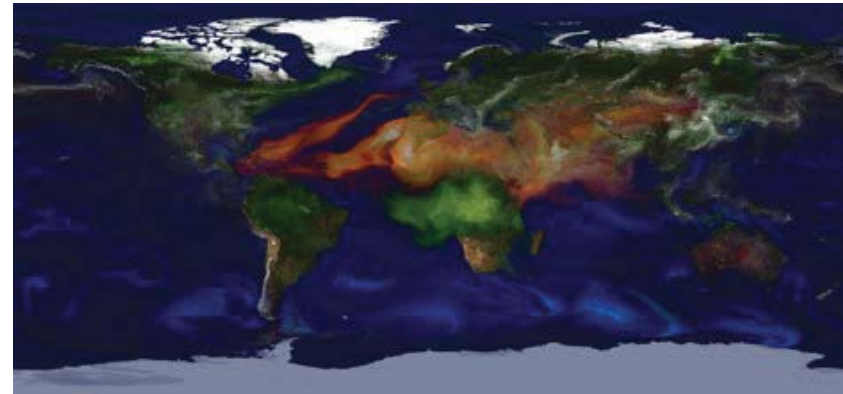


Sept
2012

PACE Simulator



- GEOS-5 non-hydrostatic 7 km atmosphere with GOCART aerosols
- Coupled to GEOS-5 10 km ocean component with biogeochemistry
- Simulation of
 - Water leaving radiances
 - t.o.a. reflectances



Concluding Remarks



AEROSOLS IN GEOS-5

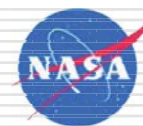
- The GEOS-5 Earth Modeling System includes data assimilation of its major components
- Aerosols are an integral part of the GEOS-5 NRT and re-analysis systems
- GEOS-5 OSSE activities in support of new NASA observing missions
 - Builds on NWP capabilities, extends it to constituents and other components

GEOS-5 EVOLUTION

- Aerosol/cloud processes evolving from bulk to modal/2-moment schemes
- Aerosol assimilation evolving into a EnKF sub-system within the atmospheric 4D-EnVar

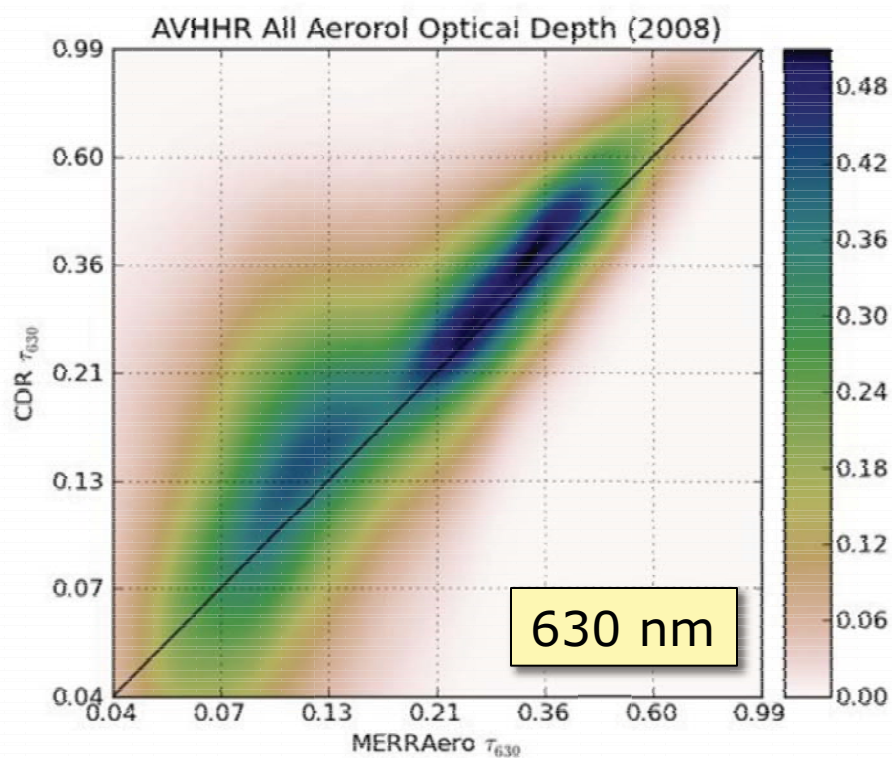


Extra Slides

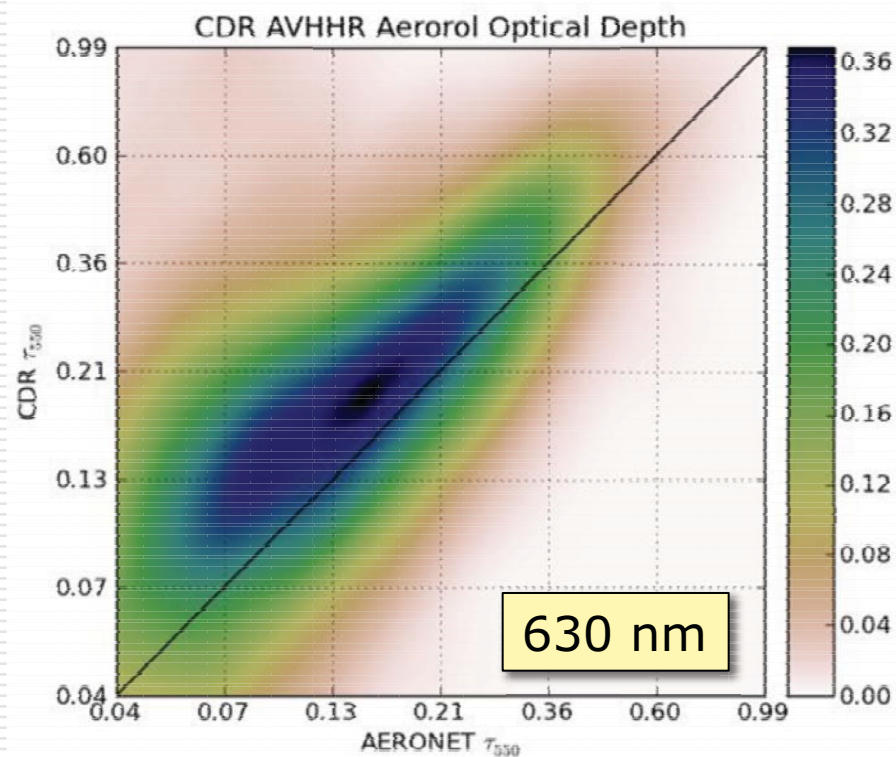


AVHRR NOAA CDR AOD

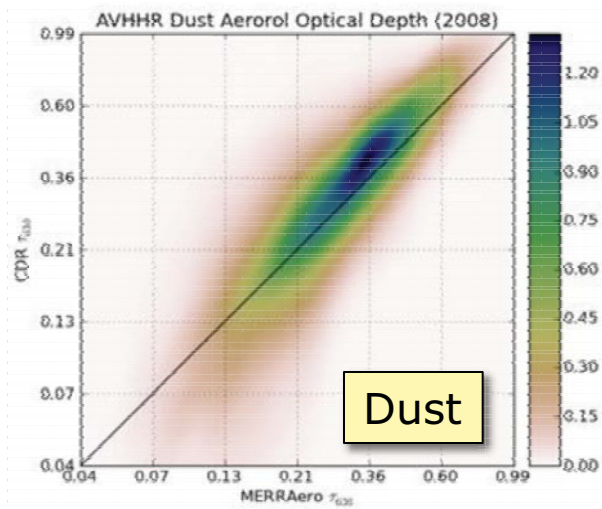
MERRAero, AERONET Comparison



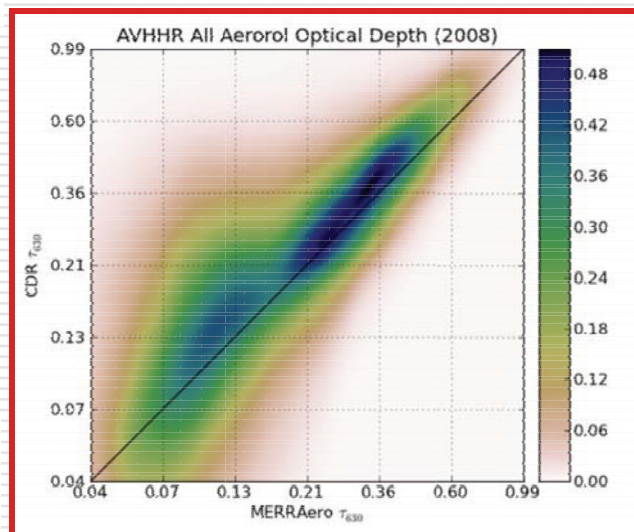
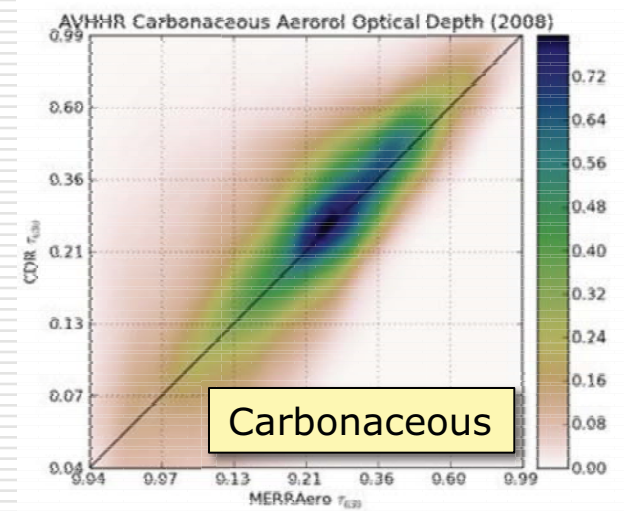
MERRAero



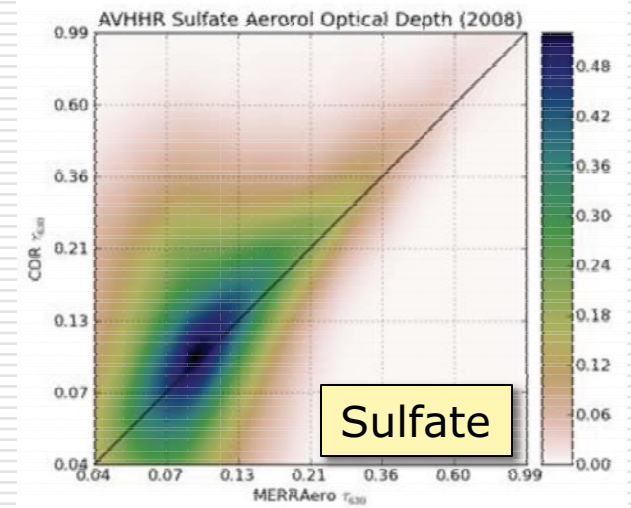
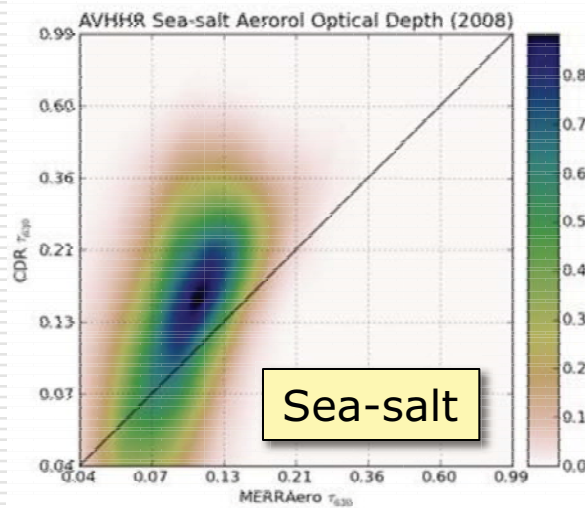
AERONET



CDR: 2008

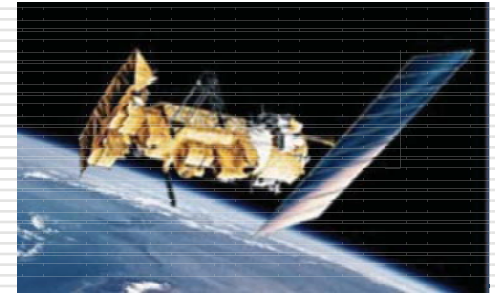


Multiple Species



PATMOS-x

AVHRR Pathfinder Atmospheres - Extended



PATMOS-x Dataset

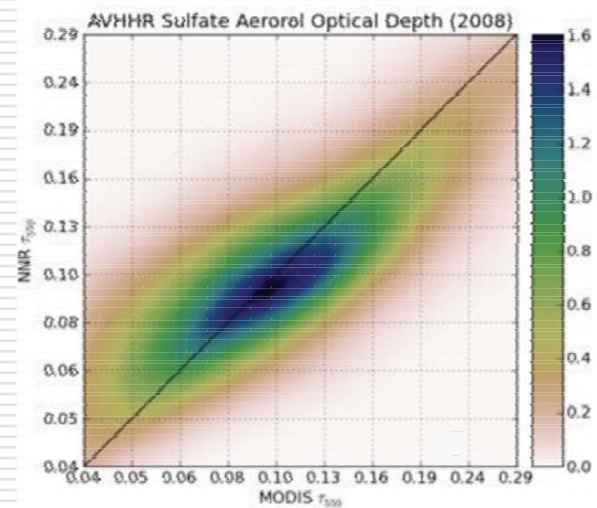
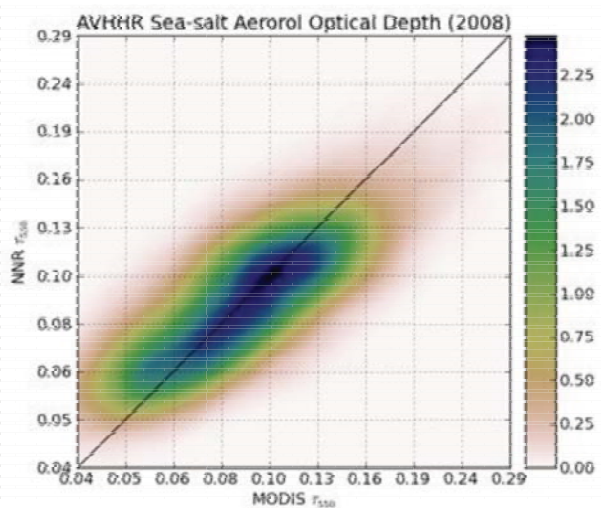
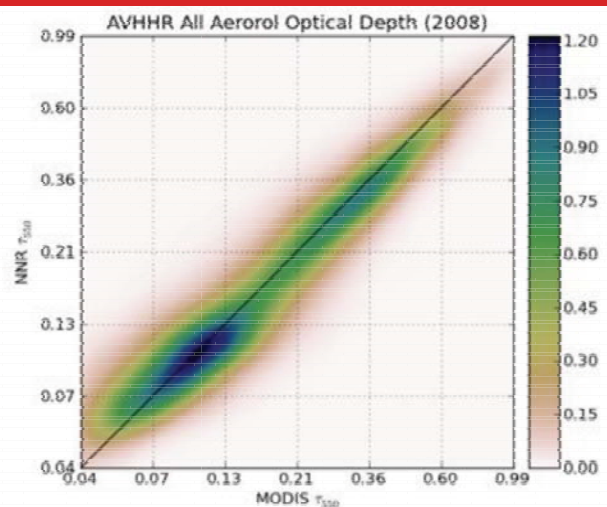
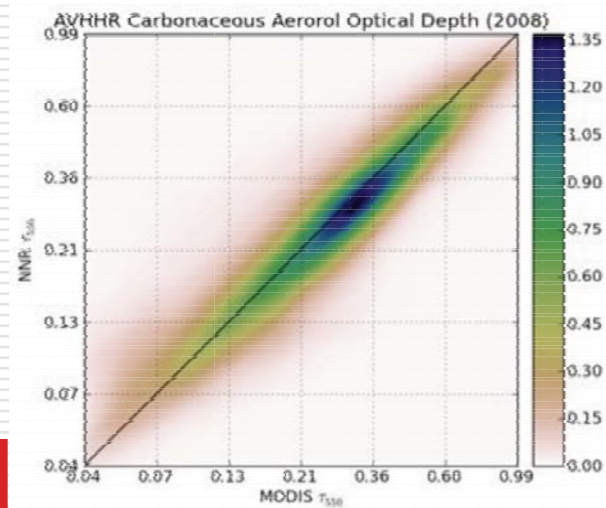
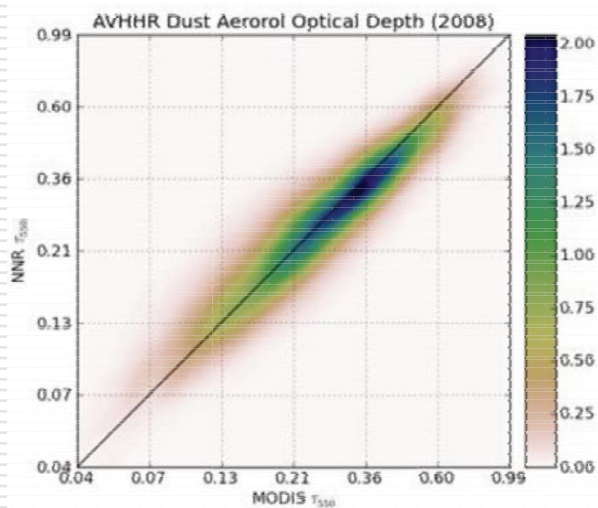
- ❑ Version 5 Level 2B
- ❑ 0.1 degree sampling (not average)
- ❑ Period: 1978-2009
- ❑ Inter satellite calibration (MODIS reference)
- ❑ Bayesian probabilistic cloud detection (CALIPSO reference)
 - **cpd <0.5%**

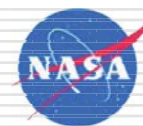
Neural Net Retrival

- ❑ **Ocean** Predictors
 - TOA Reflectances
 - **630 and 860 nm**
 - TPW
 - Ocean albedo (wind)
 - Solar and sensor angles
 - GEOS-5 fractional AOD speciation
- ❑ Target:
 - AOD at **550 nm**
 - Balanced MODIS NNR

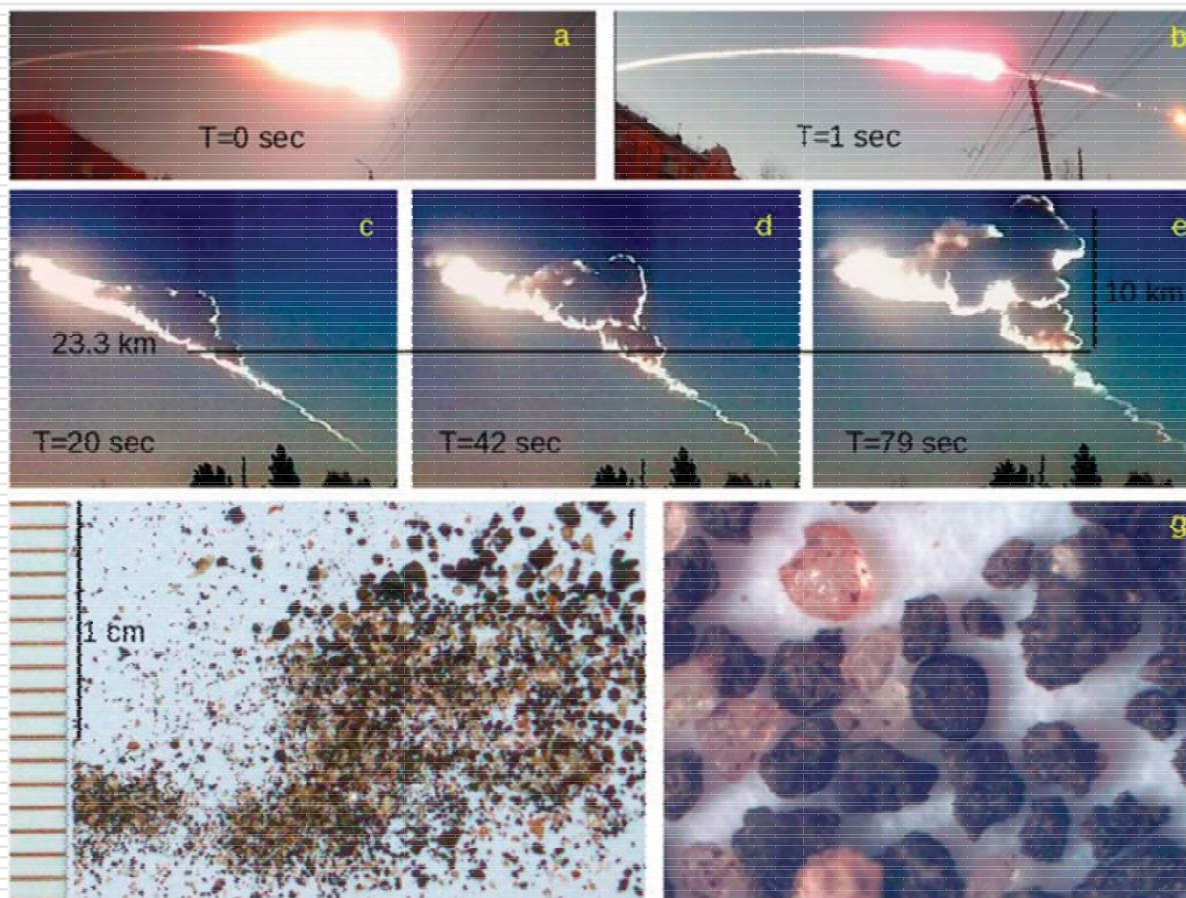
2008

Multiple Species





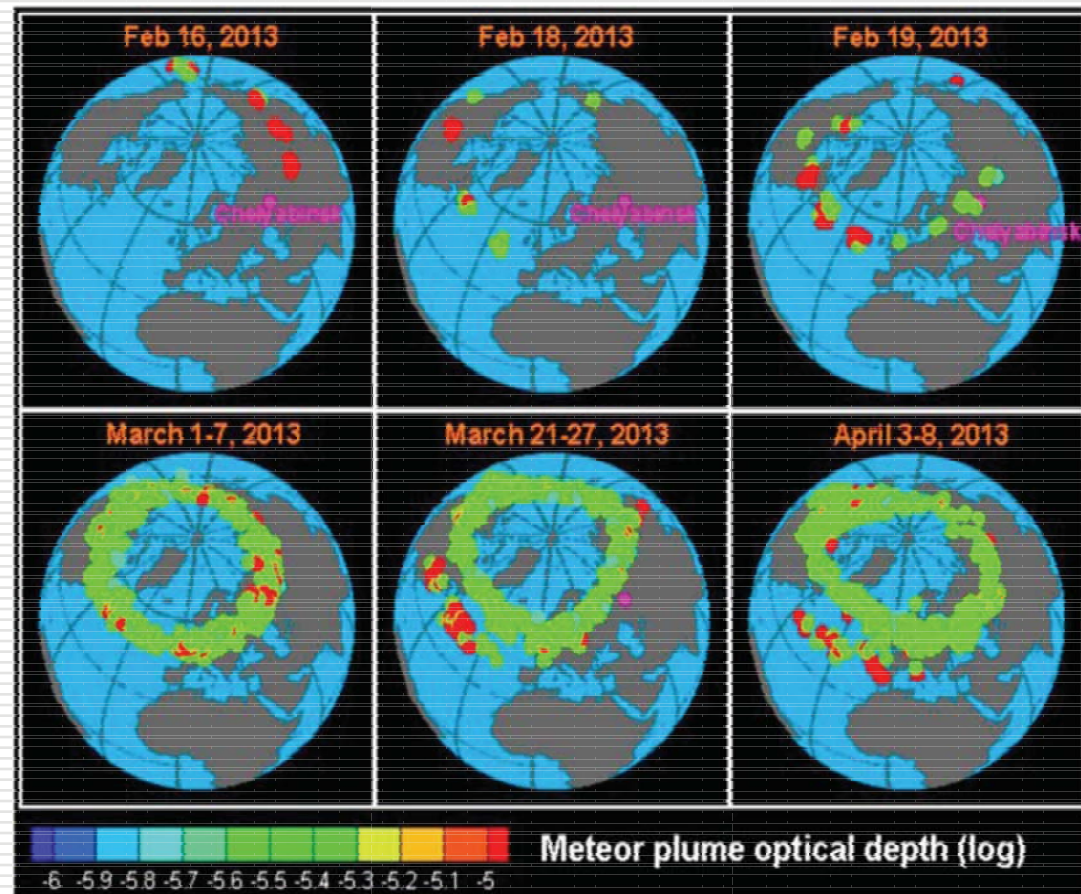
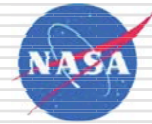
Russian Super Bolide of 2013



Gorkavyi et al., 2013 (2013)

3:20 UTC 15 February 2013

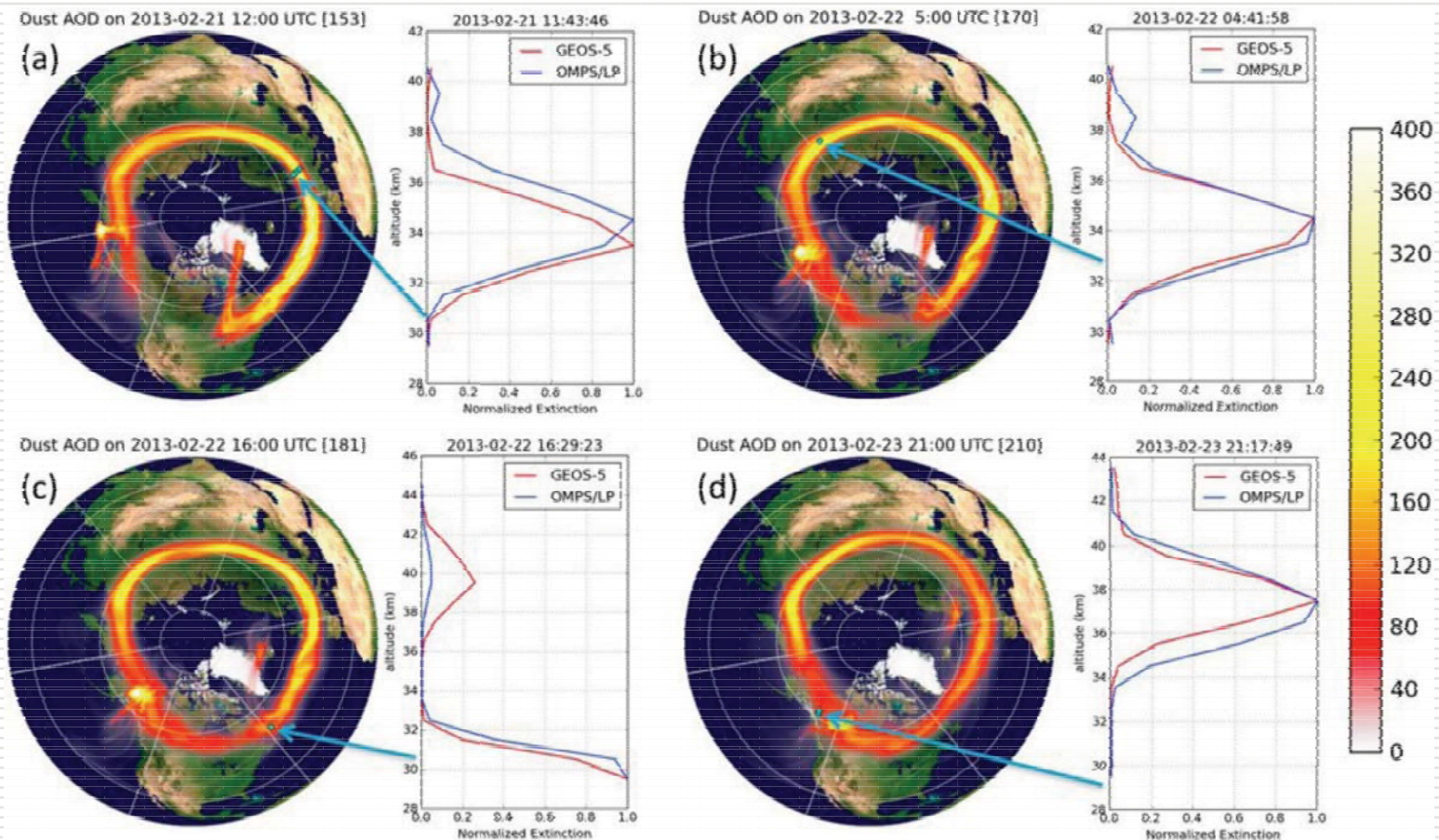
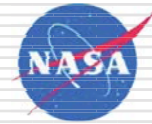
Chelyabinsk Meteor Dust Plume



Gorkavyi et al., 2013 (2013)

As seen by OMPS Limb Profiler

Chelyabinsk Meteor Dust Plume



Gorkavyi et al., 2013 (2013)

As simulated by GEOS-5